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Managing human-induced material use: adding cyclic inter-sectoral flows to Physical Input-Output Tables to analyse the environmental impact of economic activity

by

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Declaration of Authorship

I, Aleix Altimiras-Martin, declare that this thesis, titled "Managing human-induced material use: adding cyclic inter-sectoral flows to Physical Input-Output Tables to analyse the environmental impact of economic activity", is submitted according to the requirements of the Degree Committee of Land Economy.

The thesis does not exceed the regulation length of 80,000 words including footnotes, references and appendices. It is the result of my own work and includes nothing which is the outcome of work done in collaboration with others, except where specifically indicated in the text and Acknowledgements.

Signed: ____

Date: Campinas, 26th July 2015

To Carol, my inspiration

"The ideal cannot be undermined simply by pointing out that it cannot be achieved at present."

Beitz (1979, pg. 156)

"If everyone does a little, we'll achieve only a little."

MacKay (2009, pg. 3)

"But, as I think back, it was the bedder who showed a more subtle grasp of the core truths of human exchange."

Judt (2010, pg. 109)

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Abbreviations

BGCC	**B**io**G**eo**C**hemical **C**ycle
C2C	**C**radle-to-**C**radle
EE-IOT	**E**nvironmentally-**E**xtended **I**nput-**O**utput **T**able
EW-MFA	**E**conomy-**W**ide **M**aterial **F**low **A**ccounting
GHG	**G**reen**H**ouse **G**as
IAM	**I**ntegrated **A**ssessment **M**odel
IEA	**I**nternational **E**nergy **A**gency
IO	**I**nput-**O**utput
IOA	**I**nput-**O**utput **A**nalysis
IOT	**I**nput-**O**utput **T**able
IPCC	**I**nternational **P**anel on **C**limate **C**hange
LCA	**L**ife **C**ycle **A**nalysis
MFA	**M**aterial **F**low **A**nalysis
MIOT	**M**onetary **I**nput-**O**utput **T**able
PIOT	**P**hysical **I**nput-**O**utput **T**able
SEEA	**S**ystem of **E**conomic and **E**nvironmental **A**ccounts
SFA	**S**ubstance **F**low **A**nalysis
SiU	**S**tock-**in**-**U**se
SNA	**S**ystem of **N**ational **A**ccounts

Summary

Managing human-induced material use: adding cyclic inter-sectoral flows to Physical Input-Output Tables to analyse the environmental impact of economic activity

Aleix Altimiras-Martin

Current human activity is degrading the environment and depleting biotic and abiotic resources at unheard-of rates, inducing global environmental change and jeopardising the development of humankind. The structure of human activity determines which resources are extracted, how they are transformed and where and how they are emitted back to the environment. Thus, the structure of human activity ultimately determines the human–Earth System interaction and human-induced environmental degradation. Several theories and empirical findings suggest that a cyclic structure would lower the resource requirements and emissions of the economic system, decoupling production and consumption from their environmental impacts. However, the cyclic structure has not been fully characterised nor related to the resource requirements or emission generation estimates of environmental impacts as calculated through models representing the physical structure of the economic system.

This thesis is interested in developing tools to analyse the physical structure of the economic system and, ultimately, to develop a method to identify its cyclic structure and relate it to the environmental impact induced by economic activity. Using this new knowledge, it might be possible to reduce the environmental impact of the economy by altering its physical structure.

In chapter 3, the different methods to calculate the emissions and resources associated to a given final demand of physical input-output tables are reviewed because they gather different results; it is argued that only two are valid. Surprisingly, these two methods reveal different physical structures; these are explored using a backward linkage analysis and their differences explained. It is found that only one method is appropriate to analyse the physical structure of the economic system and this method is in fact a new input-output model capable of tracing by-products as final outputs. Also, since traditional input-output structural analyses provide aggregate measures, a visual representation of input-output tables enabling researchers to perform disaggregated structural analyses and identify intersectoral patterns is developed.

In chapter 4, a method to derive the full cyclic structure of the economic system is developed using network analysis within the Input-Output framework; it identifies the intersectoral cycles and the resources and emissions associated to cycling. It is shown that cyclic flows maximise the system throughput but lower the resource efficiency of the system vis-à-vis the system outputs. It is demonstrated that 1) the complete structure is composed of a cyclic–acyclic and a direct–indirect sub-structure, challenging the common understanding of the functioning of the structure, and 2) cycling is composed of pre-consumer cycling, post-consumer cycling, re-cycling and trans-cycling.

In chapter 5, a set of indicators are developed to capture the weight and emissions associated to each sub-structure and the sub-structures are related to the economy's resource efficiency and emissions.

In chapter 6, it is illustrated how to use the concepts, indicators and methods developed in previous chapters to identify strategies to improve the resource efficiency of the economy by altering its structure.

Finally, in chapter 7, it is suggested to refine the definition of recycling to integrate the different systemic effects of pre-consumer and post-consumer cycling and it is argued that the ideal structure of a circular, close-loop economy should minimise its pre-consumer cycling in favour of more efficient acyclic flows while maximising its post-consumer cycling.

Chapter 1

Introduction

The second world war was not only a turning point in world geopolitics but also in the way human activity affects and interacts with the environment. Figure 1.1 shows that global material consumption almost doubled between 1900 and 1950 but increased almost six fold between 1950 and 2005, i.e. the rate of global material consumption tripled after the second world war. The pattern of some emissions such as carbon dioxide emissions followed the same trend (CDIAC, 2013). These trends together with the rising population sparked the debate on the biophysical limits of the Earth System and their relationship with technology (Boulding, 1966; Georgescu-Roegen, 1971; Meadows et al., 1972; Commoner, 1972; Ehrlich and Holdren, 1972).

In 1987, the term Sustainable Development (SD) was coined to integrate and overcome these biophysical limits while improving human well-being. The main feature of SD is the systemic consideration of the different dimensions of human activity: economic, social and environmental (WCED, 1987). The main challenge to achieve SD is posed by the trade-off between the economic and environmental dimensions: while economic development and associated growth improves human well-being, it also degrades the environment, reducing well-being.

Technological evolution has been identified as a potential solution to mitigate or even cut environmental degradation (Foray and Grübler, 1996). It has been demonstrated that it can offset the trade-off between the economic and environmental dimensions (Porter and Van der Linde, 1995). In fact, it is required that human activity produces and consumes goods and services differently, in a more resource efficient manner, so that human activity "fits" within the biophysical limits of the Earth System (Ayres, 1994a; Porter and Van der Linde, 1995). Some systemic solutions for a more resource efficient production-consumption structure have been developed within the field of Industrial Ecology (Ayres, 1994a, 1996; Ayres and Ayres, 2002). However, these systemic solutions

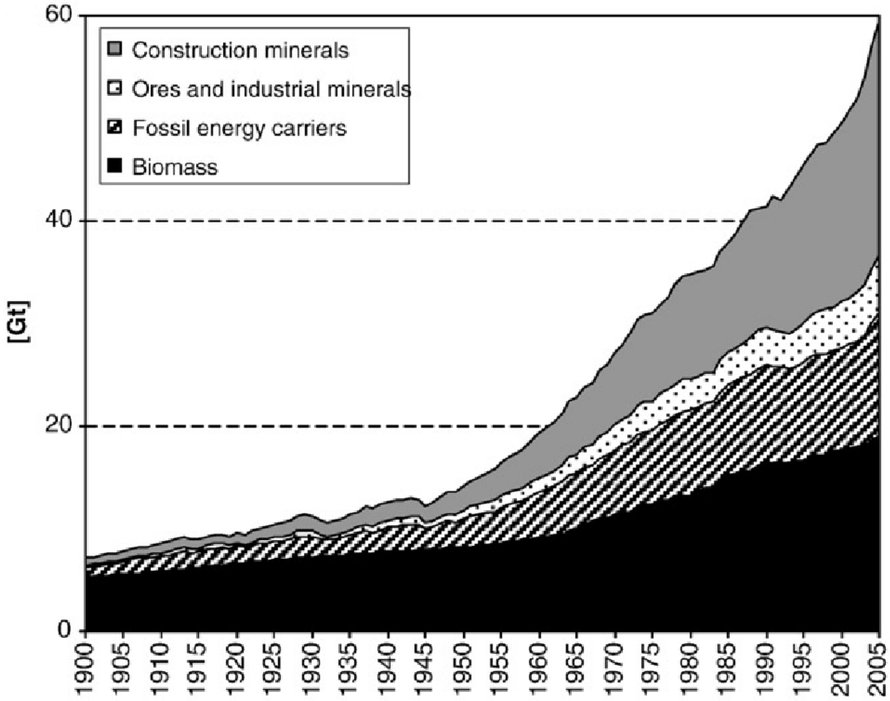

FIGURE 1.1: Materials use by material types in the period 1900 to 2005 in gigatons per year (Krausmann et al., 2009, fig. 1a).

are based on Life Cycle Analysis methods, which help identifying potential improvements in the system but are not suited to model the systemic effects at macroeconomic level. Analytical tools to assess systemically the physical structure and resource efficiency of economies are still missing or under development, mostly due to the significant limitation in data and mathematical representations of the physical structure of the economic system. In this thesis, such tools are developed and the macroscopic resource efficiency is related to relevant structural features, making it possible to improve the resource efficiency of the economy by modifying its structure.

However, before discussing potential structural changes to mitigate the environmental impact of the economic system, it is important to understand what are the main environmental challenges that current societies face and what constitutes environmental degradation. Section 1.1 and 1.2 provide correspondingly a succinct explanation for each aspect.

1.1 The tightening of biophysical limits

The biophysical boundaries of the Earth System pose limitations on the type and amount of resources that human activity can extract and on the type and amount of emission that human activity can generate. The Earth System generates biotic resources (e.g. forests and fish stocks) at different rates, depending on the ecosystem properties — i.e. each ecosystem has a different regenerative capacity. Similarly, the Earth System can absorb different emissions at different rates, i.e. different ecosystems have different absorptive capacities. The regenerative and absorptive capacity constitute the carrying capacity of the Earth System. The biophysical boundaries also include the abiotic and fossil fuel reserves, which are given in finite amounts and can potentially lead to scarcity issues. In this sense, achieving SD remains a great challenge because several environmental and resource scarcity issues threaten human progress (Gordon et al., 2006; Koning et al., 2008; Cordell et al., 2009; Rockstrom et al., 2009; Almeida and Silva, 2009). Thus, accommodating to the biophysical limits of the Earth system constitutes one of the main challenges that societies face.

For example, despite the technological advances and international political coordination, the emissions of greenhouse gases have risen yearly since the industrial revolution[1] (CDIAC, 2013) to levels unprecedented in at least the last 800,000 years, inducing climate change (IPCC, 2013). This trend poses several simultaneous threats to humankind: the physical effects of climate change (e.g. floods, droughts and sea level rise) affect biological systems (e.g. terrestrial and marine ecosystems), which in turn affect food production, water supply, livelihoods, health, and the economics of several regions (IPCC, 2014a). Similarly, emissions associated to the use of fertilisers and fossil fuel burning are altering global flows of nitrogen, leading "to a host of environmental problems, ranging from eutrophication of terrestrial and aquatic systems to global acidification" (Gruber and Galloway, 2008).

Biotic resource depletion is either due to extraction rates surpassing the natural regenerative rates (e.g. fish stocks (UNEP, 2012) and land (Mosier et al., 2004) are overexploited) or to the degradation of the environment where the resources are located (e.g. eutrophication of rivers and estuaries, reducing the available fish stocks). In many cases, renewable resources (e.g. fisheries and forests) are key for the survival of humans since they provide food (e.g. fish and crops) and materials vital for human activity (e.g. wood, resins, rubber, cotton and paper). The depletion rates have increased as indicated in figure 1.1; for example, in 1987, 15% of global fish stocks were classed as collapsed and, in 2007, they roughly doubled to 30% (Brauch et al., 2009), and forest loss has remained alarmingly high (UNEP, 2012).

Abiotic resources such as fossil fuels[2], phosphorus and copper are also key for human development and survival. Fossil fuels provide energy for industry, households and

[1]Except in 2009, due to the worldwide economic crisis.

[2]Fossil fuels are derived from biomass and can also be considered biotic resources. However, they are considered abiotic since, in their confined status, they are unlinked from the contemporary biosphere cycles.

transportation. Oil is particularly vital for humans since it is the energy vector used for transportation (the other fossil fuels are not well suited for this use) and for materials purposes, since it is the base for synthetic chemistry to produce plastics, solvents and pharmaceuticals. Many scholarly and technical reports project the decline of production within the first half of the 21st century as these resources are depleted (Almeida and Silva, 2009). Phosphorus is a vital nutrient for crops that cannot be substituted by other fertilisers. Its peak production is estimated to be around 2030 (Cordell et al., 2009), jeopardising food production, especially when the world population is estimated to surpass nine billion people by 2050 (UN, 2009). Also, copper resources are expected to be depleted by the end of the 21st century assuming today's developed-country level of services for copper worldwide (Gordon et al., 2006). Copper scarcity would jeopardise technological development since it is a key metal for electric and electronic equipment as well as for industrial uses, and the substitution with other materials with similar properties such as aluminium is not straight forward (Messner, 2002).

An extra complication is that environmental degradation, biotic and abiotic resource depletion issues are interrelated. For example, increasing food production using current techniques would require increased use of fertilisers and land, so mitigating food poverty might aggravate other environmental issues such as global eutrophication or biodiversity loss (Sutton et al., 2013). Similarly, trying to develop a new technological infrastructure (e.g. electric cars and renewable energy power-plants) to be less dependent on oil and fossil fuels, and emit less pollutants will increase the dependence on copper, whose ore reserves are limited (Gordon et al., 2006).

In short, despite technological innovation and international political coordination, human activity has increased its footprint on the Earth System, with increasing rates of resource extraction and emission generation, which in turn are reshaping the Earth System and jeopardising the development of humankind. It is thus of chief importance to find ways to carry on human activity without degrading the environment and depleting natural resources. More importantly, current approaches to mitigate environmental degradation are challenged by the increasing rates of resource extraction and pollutant emissions, suggesting that a systemic, structural change is required in the production–consumption system.

1.2 Human activity is exceeding the carrying capacity of the Earth System

Environmental degradation is usually seen as a panoply of phenomena (as seen in the previous section) affecting different components of the environment at different rates and scales. However, from an Earth System perspective, environmental degradation can be summarised as the disruption of the natural biogeochemical cycles. The main ideas related to this approach are introduced below (and reviewed in detail in section 2.2).

Human activity is degrading the environment and depleting biotic resources because it surpasses the carrying capacity of the Earth System (Rees, 1996; Steffen et al., 2005). Regarding biotic resources, fish stocks are depleted because fish catches exceed the regenerative capacity of the ecosystems producing them; part of the deforestation occurs because wood is collected faster than its growth rate. Regarding environmental degradation, human-induced emissions degrade the environment because they exceed the absorptive capacity of ecosystems, even if the emissions stem from use of biotic resources such as food (e.g. eutrophication caused by waste waters). In this sense, emissions associated to abiotic resources and fossil fuels have even greater impacts because these materials are extracted from confined sources (e.g. mines) and released to other parts of the Earth System (e.g. atmosphere) which are not able to absorb them, disrupting systematically the natural cycles. In fact, two of the most pressing environmental issues are related to the extraction and use of abiotic resources: climate change (use of fossil fuels) and global eutrophication (use of fertilisers) (Rockstrom et al., 2009).

Additionally, the environmental degradation derived from exceeding the carrying capacity of the Earth System could be irreversible (Rockstrom et al., 2009; IPCC, 2013) and even lead to abrupt environmental change, constraining and jeopardising human development (Steffen et al., 2005; IPCC, 2014b).

The carrying capacity of the Earth System is being surpassed because human-induced material flows, i.e. resource extraction and emission generation, either exceed the natural mobilisation and transformation rates (Baccini and Brunner, 1991; Vitousek, 1997) or are released in forms or in locations that disturb the natural (biogeochemical) cycles of the Earth System (Melillo et al., 2003, chap 3). In other words, humans dominate the Earth System (Vitousek, 1997) and have deeply modified the terrestrial biosphere, from mostly wild to mostly anthropogenic, passing the 50% mark early in the 20th century (Ellis et al., 2010).

So, in order to explore whether it is possible for humans to continue their activity without exceeding the carrying capacity of the Earth System, the focus of study must be shifted towards human activity itself, since it is the human-induced material flows that degrade the environment. This research will take this approach, i.e. it is solely interested in the material flow — *physical* — structure of the economic system.

1.3 The need to analyse and characterise the physical structure of the economic system

The physical structure of human activity determines which resources are extracted, how they are transformed and where and how they are released or emitted back to the environment. Thus, it is the structure of human activity that ultimately determines the human–Earth System interaction and human-induced environmental degradation. Consequently, the key to exploring whether it is possible for humans to continue their activity without exceeding the carrying capacity of the Earth System is to focus on the structure of human activity.

The current structure of human activity is linear: it extracts biotic and abiotic resources, transforms them into goods, uses them, and disposes the used goods back into the environment. Boulding (1966) already recognised this feature of the economic system and named it as the "Cowboy Economy". He also imagined an ideal economy whereby resources would be recycled within the economy and through the environment without degrading it. He named it the "Spaceship Economy" but he did not formalise such structure, or relate it to quantitative macroeconomic models that capture systemic properties.

At that time, environmental sciences' strategy was to address environmental degradation in a linear way, whereby environmental issues were typically tackled with end-of-pipe (EoP) solutions (Foray and Grübler, 1996). These solutions are cheaper and easier to develop and implement, since only minor changes are introduced in the activity at the emission point (e.g. to filter emissions before releasing them instead of changing the feedstock and process technology), and the existing institutions and system structure favour this type of technological development (Kemp and Soete, 1992; Nemet, 2009). However, an EoP approach only shifts the issue, since pollutants are redirected somewhere else causing less harm (e.g. sulphur from flue gases are filtered and landfilled); and the overall resource efficiency is low, since many materials used during production are later discarded or released as emissions.

However, such approach has been shifting to a more dynamic one, where systemic technological change might improve economic and material efficiency performance (Foray and Grübler, 1996; Porter and Van der Linde, 1995). Such type of technological change is based on the principles developed within the Industrial Ecology field, such as Pollution Prevention, Cleaner Production and EcoDesign (Júnior and Demajorovic, 2013). Accordingly, current technical reports aiming to mitigate environmental degradation and resource depletion call for a shift towards different technologies (IEA, 2011; IPCC, 2014a), implying a change in the physical structure of the economic system.

Different technologies require different feedstocks, which are transformed and released differently, altering the original physical structure of the economic system. Thus, characterising and linking the structural features of the economic system to its environmental impacts and identifying them is vital to inform a transition towards a different economic and technological regime or structure. Current technical reports have focussed on the environmental impacts caused by the different sectors of economic activity and the drivers inducing them, such as population, affluence and technology (Steffen et al., 2005; IEA and OECD, 2004; IPCC, 2007b; IEA, 2011; IPCC, 2014a), but they have not explicitly studied how the physical structure of the economic system affects its environmental performance. The first logical step to link environmental impacts to selected structural features (e.g. degree of cycling) is to develop the theoretical understanding on how to analyse the physical structure of the economic system, a task that will be undertaken in chapter 3.

1.4 The need to characterise the cyclic structure of the economic system

Several authors have suggested that an economy with recycling as its main structural feature would reduce materials, energy and emissions in order to produce the same amount of products (Boulding, 1966; Ayres, 1996; Allwood et al., 2010). This approach has been backed by numerous life cycle studies (WRAP, 2010). Even an "ideal" structure for the economic system based on a cyclic structure, a "cradle-to-cradle" material flow structure, had been suggested by McDonough and Braungart (2002), whereby all materials are either re-used within the economy or emitted to the environment without causing environmental degradation. However, despite the relevance of the economic system's cyclic structure to mitigate environmental degradation and resource extraction (i.e. to increase the economic system resource efficiency), it has only been studied quantitatively at process or sectoral level (Bailey et al., 2008) and characterised partially: only within intersectoral interactions (Ulanowicz, 1983), or aggregately (Finn, 1976; Bailey et al., 2008). This is in large measure because cycling is a complex phenomenon requiring systemic analysis of the physical structure of economies, which has had significant limitations in data and mathematical representations.

Thus, the full explicit characterisation of the cyclic structure of the economic system is still unknown (i.e. the resources and emissions associated to the cyclic structure) and its relationship with the system features has not yet been established (e.g. how the cyclic structure affects emission generation and resource extraction). It is not yet clear, therefore, how structural changes in the cycling paths will influence the environmental impact of economies.

Finding and analysing the relationships between the (cyclic) structure and the resource requirements and emission generation of the economic system, and characterising the key structural features mitigating them would enable policy makers to devise and guide technological transitions informedly towards a more resource efficient economic system. And a more resource efficient economic system is more sustainable because it generates less emissions (mitigating the environmental impacts associated to those emissions), and it requires less resources (mitigating the environmental impacts and scarcity issues associated to the extraction of these resources).

1.5 Research aims and objectives

1.5.1 Aim of the thesis

The aim of this thesis is to identify how to improve the resource efficiency of the economy by altering its physical structure. Improving the resource efficiency implies that less natural resources will be used and less emissions will be generated to produce the same amount of final goods. Therefore, a more resource efficient physical structure mitigates human-induced environmental degradation while maintaining the same level of final consumption. In other words, it induces an absolute decoupling between the production/consumption and environmental impact.

However, in order to identify how to improve the resource efficiency of the economy through structural change, several intermediate milestones need to be fulfilled. Each subsection below corresponds to the aims and objectives pursued in each of the chapters following the literature review (chapter 2).

1.5.2 Aim of chapter 3: to understand how to analyse the physical structure of the economic system

Before developing complex decompositions to identify the cyclic structure of the economic system, the analytical methods or models enabling researchers to analyse the physical structure of the economies need to be well understood, otherwise basic structural analysis could not be performed. The aim of chapter 3 is precisely to understand how to analyse the physical structure of the economy represented by Physical Input-Output Tables (PIOTs) and using Input-Output methods and models.

The construction of PIOTs dates back from the late 90s, however it was not until 2003 that the first analytical applications were developed; several methods were suggested, each gathering different results (c.f. section 3.2.1). Therefore, the first research objective is to explain which methods/models can be applied to PIOTs and which cannot (c.f. section 3.2.2).

In section 3.2.2, it is shown that only two methods can be used to calculate the resources and emissions associated to any given level of final demand; however, it is also shown that each methods reveals a different inter-sectoral structure (i.e. a different technical coefficient and Leontief inverse matrix). Therefore, the second research objective is to explain the differences between the two set of structures and identify which structure represents the actual physical structure underlying economic activity.

Structural analyses such as linkage analysis provide aggregate measures that can mask underlying structural patterns. In particular, the same backward linkage measure might hide different inter-sectoral relationships; similarly, different backward linkage measures might have the same composition of inter-sectoral flows. However, to identify the structural patterns between all sectors requires to analyse all inter-sectoral flows at once, which is extremely challenging given the amount of data contained in IOTs. Therefore, the third research objective is to develop a visual representation enabling researchers to perform disaggregated analyses to identify visually structural patterns underlying inter-sectoral relationships (c.f. section 3.3).

1.5.3 Aim of chapter 4: to identify the cyclic structure of the economic system

The second aim of the thesis is to identify the cyclic structure underlying the physical structure of the economic system. This constitutes the main contribution of the thesis because: 1. a decomposition revealing the complete cyclic structure had never been developed previously, and 2. in order to achieve it, a new understanding on how the sub-structural components are related to each other is developed.

Currently, only one method is available to identify inter-sectoral cycling; however, it has computational limitations (c.f. section 4.2.1) and over-estimates level of cycling (c.f. section 4.2.2). Hence, the first research objective is to develop an algorithm/method to identify the inter-sectoral cycling removing the computational limitations previously identified and avoiding over-estimating the level of inter-sectoral cycling.

Once the level of cycling within the system is established, the second research objective is to identify the resources and emissions associated to the cyclic structure.

Then, the third research objective is to identify the full cyclic structure. Although this might seem a trivial task since at this point the inter-sectoral cycles and associated primary resource and emissions are known, it is found that part of the inter-sectoral flows that were previously thought to be acyclic also belong to the cyclic structure. Therefore, the previous understanding on how the structure of dissipative systems works is misleading and a new theoretical understanding on how to decompose the physical structure of the economy is suggested in section 4.5.1. The new theoretical understanding it put into practice by developing a method identifying the full cyclic structure of a PIOT in section 4.5.2.

1.5.4 Aim of chapter 5: to develop indicators and relationships relating the structural features of the system to their environmental impact

Once the full cyclic structure (and other sub-structures) have been identified, the next research aim is to relate the sub-structural components of the system (e.g. the inter-sectoral cyclic or indirect flows) to their environmental impact. The underlying idea is to develop analytical tools that can be used to assess the environmental performance of the structure of the economy, which in turn would enable researchers and policy-makers to guide structural changes to alter the physical (and technological) structure to reduce the environmental impact of the economy.

So far, the cyclic structure has only been related to its environmental impact through the use of inaccurate proxies. E.g. by using the amount of inter-sectoral cycling as proxy for the environmental impact associated to cycling itself (Bailey et al., 2004b), which is not a good proxy because a high level of cycling does not necessarily induce a high level of emissions. Therefore, the first research objective is to develop a set of indicators informing researchers about the weight of each sub-structural component and also quantifying the environmental impact associated to each sub-structural component.

Currently, the determination of more efficient (cyclic) structures is done by comparing different structural options (Bailey et al., 2004b, 2008) because it is unknown how the different sub-structural components affect the overall performance of the system. Therefore, the second research objective is to relate the different sub-structural components and features (e.g. sectoral efficiencies) to the overall performance of the economic system. Only then it will be possible to determine directly (i.e. without requiring comparative analysis) which sub-structural components are to be minimised or maximised in order to increase the resource efficiency of the system as a whole (i.e. reducing the primary resource requirements and emission generation).

1.5.5 Aim of chapter 6: to illustrate how to improve the resource efficiency of the economy through structural change

Finally, it is sought to illustrate how to use the previously developed methods, concepts, indicators and relationships to analyse the productive structure of the economy to develop strategies to improve its resource efficiency (in turn mitigating its environmental impact).

The first objective is to show the kind of analysis that can be performed using the IO methods reviewed and developed in chapter 3 and the decomposition suggested in section 4.3, and to highlight the kind of strategies that can be developed using this type of analysis.

However, conventional structural analyses cannot fully explain the macroscopic behaviour of the system given its mesoscopic properties. E.g. the macroscopic resource efficiency is very low compared to the sectoral (mesoscopic) resource efficiencies, so what is lowering the overall resource efficiency of the system?

The second objective is to explain the macroscopic behaviour of the economy by using use the decomposition, indicators and relationships developed in chapters 4 and 5 and, more importantly, to illustrate how to identify the different options to improve the resource efficiency of economy by altering its structure.

1.6 Structure of the thesis

This thesis contains seven chapters including this introduction (chapter 1). The following paragraphs summarise what each chapter covers.

In chapter 2 — the literature review —, it is first sought to understand what environmental degradation is (section 2.2), so as to select an appropriate level of analysis to relate environmental degradation to economic activity. Then, the structure of economic activity is studied and related to the technological structure and environmental degradation and resource extraction in section 2.3. In section 2.4, several accounting and modelling frameworks are reviewed to select an appropriate framework to study the physical structure of economies. In section 2.5, current approaches and theories to mitigate environmental degradation and resource extraction are reviewed and, in section 2.6, special attention is given to the methods quantifying the level of cycling and its structure.

In chapter 3, the different methods used to calculate the emissions and resources associated to a given final demand of physical input-output tables are reviewed in section 3.2.1 because they produce different results; the reasons for these differences are clarified and it is explained why some of the previous methods produce inaccurate results in section 3.2.2. However, since the two methods that produce the same (correct) emissions and resources results reveal different structures, the two structures are compared and analysed in section 3.2.4 using a backward linkage analysis and the different results are explained; the resulting analysis shows that only one method is appropriate to analyse the physical structure of the economic system and this method is in fact a new IO model making it possible to analyse IOT generating several simultaneous final outputs. In section 3.2.5, to increase the analytical potential of PIOTs, both (correct) methods are generalised to be able to analyse PIOTs with several simultaneous emissions. Also, since traditional input-output methods such as linkage analysis provide aggregated structural indicators (one measure per sector), a visual representation of input-output tables is developed in section 3.3 enabling researchers to perform disaggregated structural analyses (by revealing the composition of the measure) to help identifying specific structural features or patterns.

In chapter 4, a new structural decomposition which challenges the previous understanding of the cyclic structure is suggested — this constitutes the main advancement of this research. To start with, a new method to identify intersectoral cycling is suggested in section 4.2 because the previous method was inaccurate and computationally restricted. Then, the product-based decomposition of a PIOT — required to identify intersectoral cycling accurately — is formalised in section 4.3. In section 4.4, the resources and emissions associated to intersectoral cycling are calculated to be able to calculate the full cyclic structure; in this section it is also demonstrated that cycling is constituted by pre-consumer and post-consumer cycling, each having opposite systemic effects regarding the resource efficiency of the system. Only then, in section 4.5, it is explored how to extract the full cyclic structure from the rest of the structure. In section 4.5.1, it is found that the structure is composed of two intertwined sub-structures: the cyclic-acyclic and the direct-indirect. Following this new understanding, in section 4.5.2, a new method to derive the full cyclic structure of the economic system is developed using network analysis within the Input-Output framework. It identifies the full cyclic structure (i.e. the intersectoral cycles and the resources and emissions associated to cycling) and also the other structures associated to the other sub-structural components (acyclic, direct and indirect) within a PIOT.

In chapter 5, the relationship between *pre-consumer* cycling and the economic system features are established, i.e. the pre-consumer cycling is related to the system emissions, resource requirements and resource efficiency. It is formally demonstrated that pre-consumer cycling affects the system properties differently than post-consumer cycling. To start with, in section 5.2, the different levels of observation within a PIOT are examined so as to understand how to define the macroscopic behaviour of the system compared to its underlying mesoscopic (sectoral) structure. Then, in section 5.3, an indicator set quantifying the weight and environmental impact of the cyclic and indirect sub-structures are devised. Finally, in section 5.4, a set of relationships between the different sub-structures and the emissions and resource efficiency of the economy are established. In section 5.4.1.1, it is shown how to calculate the theoretical maximal resource efficiency of the economy given its sub-structures.

In chapter 6, a case study is provided to illustrate how to use the different indicators and methods developed in previous chapters to inform policy makers how to reduce the overall and selected emission generation (and resource extraction) by altering the physical structure of the economy, in particular by minimising pre-consumer cycling. In section 6.2, it is first sought to understand the structural features that are driving the emissions In particular, in section 6.2.1, a conventional IOA is performed to establish which final demand is inducing more emission generation and resource consumption. Then, in section 6.2.2, it is shown how to use the new decomposition to relate the level of emissions to the level of intersectoral cycling. This relationship explains the reduced macroscopic resource efficiency of the economy compared to the much higher mesoscopic (i.e. sectoral) resource efficiencies — an effect which could not be explained before identifying the full cyclic structure of the economy. Finally, in section 6.3, it is illustrated how to identify intersectoral flows to be modified to improve the resource efficiency of the economy or reduce the emission of selected emission types.

Finally, in chapter 7, the findings and results of previous chapters are discussed and contextualised in the current literature. The main advancements of the thesis are discussed first in section 7.2. In this section, the findings of chapters 4 and 5 are discussed together since both chapters provide theoretical and methodological advancements related to the identification of the cyclic structure and its systemic effects. In section 7.3, the new understanding developed in chapter 3 regarding the IO methods and models that can be applied to PIOTs are discussed. In section 7.4, the circular diagrams that are developed in section 3.3 are discussed. Finally, in section 7.5, it is discussed how to expand the current framework to represent the physical structure of the economy more comprehensively as well as some limitations of the analytical framework presented in this thesis.

Note that the structure of this thesis does not correspond exactly to the traditional Introduction, Methodology, Results and Discussion structure because the advancements developed in this thesis are mostly theoretical and methodological. Chapter 1 constitutes the introduction and chapter 2 is the literature review. Chapter 3 is a methodological chapter reviewing, re-interpreting and further developing IO methods and models applicable to PIOTs although it contains a self-contained analytical application in section 3.2.4 to illustrate that only one model is appropriate to analyse the physical structure of the economy. Chapter 4 is the main methodological chapter developing the understanding and methods to develop the structural decomposition able to identify the full cyclic structure of the economic system; it contains some numerical examples to illustrate the suggested developments. Chapter 5 is also a methodological chapter since it shows how to build an indicator set conveying how the different sub-structural components affect the system behaviour and, also, the structural sub-components are mathematically related to the emissions and resource efficiency of the economy. Chapter 6 is an illustrative example of how to apply the previously developed methods and can be considered a results chapter. The methods and results are discussed in the conclusion chapter 7.

Coming back to the initial issue introduced in this section, this thesis provides a new set of tools enabling planners and policy makers to identify which components of the economic structure should be modified (i.e. technologically improved) to mitigate systemically the environmental impact of the economic system (i.e. to reduce its resource requirements and emission generation), reducing its impact on the Earth System and alleviating the tightening of the biophysical limits in which current societies live. The advantage of this method is that greater systemic effects are detected compared to traditional methods; in particular, it identifies which sub-structural components generate most emissions at system level (and require more resources) and which are the key material flows constituting these sub-structures. This allows policy-makers to identify and subsequently study which technological changes should be performed to change the underlying technological structure.

In this sense, the developments and results of the analysis in chapter 3 are key since they constitute an advance in the theoretical understanding and development of methodologies within the Input-Output framework appropriate to model and analyse the physical structure of the economic system.

More importantly, the developments in chapter 4 represent a crucial advance in theoretical understanding of how the structure of the economic system works since it is demonstrated that the structure is in fact constituted by four intertwined sub-structures; this constitutes the main contribution of this research. This new understanding is used to develop a method to identify the cyclic, acyclic, direct and indirect sub-structures within a Physical Input-Output Table. Additionally, in chapter 5, it is developed an indicator set aiming to capture the weight and environmental impact of these structures and the formal relationships relating these structures with the system environmental's performance (i.e. its resource efficiency).

Such developments enable societies and policy-makers to assess the physical performance of the economic system. In particular, to devise and monitor industrial and environmental policies aiming to improve the overall resource efficiency of the economic system (or to mitigate selected emissions) by altering the structure of the economic activity rather than limiting the production of final goods and services.

Chapter 2

The physical structure of economies as determinant of human-induced environmental degradation and natural resource depletion

2.1 Introduction

As discussed in the previous chapter, the main challenge to achieve Sustainable Development is to offset the trade-off between economic development, growth and environmental degradation. Human-induced environmental degradation is due to human activity itself, through the extraction of natural resources and emission of several substances. So, unless current trends of resource consumption and emission generation are reverted, human activity will continue to degrade the Earth System, reducing the regenerative capacity of natural resources and the absorptive capacity for emissions, jeopardising the development of mankind by creating an inhospitable environment to live in.

To address this issue, this thesis aims to study how to reduce the environmental impact of economic activity by modifying the physical structure of the economy, decoupling in absolute terms human activity from environmental degradation. In order to explore that question, the following steps are taken in this literature review chapter:

In section 2.2, it is sought to understand what is environmental degradation and what is the most basic unit characterising it. The underlying idea is to identify what level of analysis is required to assess how to mitigate human-induced environmental degradation.

In section 2.3, the physical structure of the economic system is explored to understand its relationship with human-induced material flows and environmental degradation. The relationship between the physical structure and the technological structure is also explored.

In section 2.4, several modelling and accounting frameworks are reviewed. One of the frameworks is selected to analyse the physical structure of the economy.

Finally, in section 2.5, several approaches to manage human-induced material flows to mitigate environmental degradation are reviewed to identify which one has the potential to mitigate environmental degradation at the scale required and which aspects of it require further research.

2.2 What is environmental degradation? An Earth System approach

2.2.1 The biogeochemical cycles (BGCCs) of the Earth System

The Earth System can be divided into five[1] different geospheres: the atmosphere (the gaseous layer surrounding the Earth), the pedosphere (the outermost non rocky soil layer), the lithosphere (the outermost solid rock layer), the hydrosphere (the water content of the Earth, which overlaps with the previous three geospheres) and the biosphere (the living organisms of the Earth System, which overlaps with all previous geospheres), each having specific chemical and physical properties. The five geospheres transform and mobilise matter and energy within themselves and between them. These processes constitute the biogeochemical cycles (BGCC) of the Earth System (Butcher, 1992).

BGCCs include the basic elements for life — carbon, nitrogen, oxygen, and sulphur (Sigel et al., 2005) — but can potentially include any element of the periodic table, e.g. uranium (Trudinger and Swaine, 1979, Chap. 8). The chemical elements take several forms — either as pure elements but usually as chemical compounds — and can be exchanged and transformed through different geospheres. For instance, the carbon element (C) can be in solid mineral form as part of the lithosphere, can be dissolved in water as part of the hydrosphere, can be in gaseous form as part of the atmosphere and can be as organic matter as part of the biosphere or a human. The elements can cycle through different geospheres although some have preferred, more stable forms in a particular geosphere (Sigel et al., 2005; Trudinger and Swaine, 1979).

[1] Other geospheres exist, such as the asthenosphere (the weaker and hotter layer underneath the lithosphere) but are not considered since their interaction with the human-induced material flows is limited. Other geospheres can be derived from further divisions of the previously mentioned geospheres (e.g. the atmosphere can be subdivided into more homogeneous chemical parts), but such detailed classification is unnecessary for the current analysis.

Since the geospheres are spatial containers of given materials, they are usually modelled as coupled reservoirs (Butcher, 1992, chap. 4). The simplest modelling case assumes that the flows between reservoirs are linearly related to the content of the reservoir, i.e. its concentration, but non-linear relationships also exist and can be modelled (Butcher, 1992, chap. 4). The transformation and mobilisation of matter within and between the geospheres depends on the thermodynamic and chemical kinetics properties of the system they constitute, but the mobilisation and transformation processes are not necessarily in equilibrium (Butcher, 1992, chap. 5).

The type and rates of transformation and mobilisation of matter have evolved throughout time because the geospheres have changed. For example, the biosphere has evolved from basic micro-organisms to photosynthetic organisms such as plants producing oxygen, changing the composition of the hydrosphere and atmosphere (Butcher, 1992, chap. 3). This implies that there is not a default or correct composition for the geospheres but that these compositions are interlinked in an evolutionary process. However, at human time-scale, some of the reservoirs and the processes happening within them are considered to be in "steady-state of quasi-equilibrium" (Butcher, 1992, chap. 9).

2.2.2 Environmental degradation as a BGCC disturbance

All elements of the periodic table are potentially toxic for the biosphere at sufficient concentrations (Hill, 2010). Even if required for the proper functioning of organisms, they might have toxic effects when provided in excess concentrations: e.g. oxygen is required by aerobic organisms to live but an environment of pure oxygen would have toxic, even deadly, effects. Also, a shortage of any element usually present in a specific BGCC affects the biosphere with potential deadly effects. Following the same example, the lack of oxygen leads to the death of the aerobic organisms in the media; the same applies for the basic nutrients. So, in the biosphere case, it is clear that an excess or shortage of a given element or compound might disturb the BGCCs related to the biosphere.

A *disturbance* is a material flow, either natural or human-induced, that alters the composition or rate of flow of a BGCC; its effects can then cascade through several BGCCs and/or ecosystems. According to Melillo et al. (2003, chap 3):

> Disturbances are punctuated, episodic events that result in element redistribution within and between ecosystems, involving element transport between the biosphere, hydrosphere, lithosphere, and atmosphere. Disturbances redistribute and mobilise elements in ratios that frequently differ from ecosystem stoichiometries, mediate element interactions on large spatial and temporal

> scales and alter element distribution. [...] Disturbances differ in the extent and nature of element redistribution they cause because they differ in the degree to which they disrupt the chemical, physical and biological characteristics of the ecosystems. By redistributing elements, disturbances influence interactions among element cycles.

In other words, an excess or shortage of matter, i.e. an excessive variation of element concentration, disturbs the normal functioning of a BGCC. For example, a lack of oxygen can be induced indirectly in water streams by human activity releasing excess nutrients to the stream (e.g. agricultural fertilisers or waste waters). Due to the unusual excess nutrients in the stream, the population of the biosphere (i.e. living organisms) increases altering the original composition (stoichiometry) of the ecosystem, leading to overpopulation and depletion of the available oxygen. This process is known as *eutrophication*.

The BGCC have different scales — local, regional and global — and these scales are coupled (Butcher, 1992; IPCC, 2013). Thus, a local or regional disturbance might affect the global cycle. For example, human-induced *eutrophication* usually happens at local or regional scales, primarily due to excess nutrients released to water streams by agricultural activities (fertilisers) or municipal waste (waste waters). The water streams converge into the ocean spreading the local eutrophication at global level (Gruber and Galloway, 2008).

After a disturbance, an ecosystem might return to its original state or, if the altered element distribution exceeds a certain threshold, it might reorganise in a new state or regime with a new stoichiometry (Melillo et al., 2003, chap 3). For example, a severe case of eutrophication might lead to the death of species in an ecosystem, altering permanently its composition and leading it to a new state.

While it is not possible to qualify the different states of an ecosystem as necessarily good or bad states (Kay and Schneider, 1994), it is possible to determine and identify the different environmental impacts associated to anthropogenic activity degrading the ecosystem state (Rockstrom et al., 2009; Tukker and Jansen, 2006; UNEP, 2010a; van der Voet et al., 2009). However, environmental impacts are fundamentally disturbances of the BGCCs associated to a given ecosystem. E.g., acidification is due to the increased concentration of sulphur, disturbing the sulphur[2] cycle and associated ecosystems; climate change is the result of increased concentration of carbon dioxide[3], disturbing the carbon cycle and other cycles; and eutrophication is due to the increased concentrations of nitrogen and phosphorus (e.g. fertilisers) in water streams, disturbing the corresponding cycles and related ecosystems.

[2]Other substances than sulphur can also cause acidification.

[3]Climate Change is also due to other greenhouse gases affecting other BGCCs.

So, human-induced environmental impacts are due to the human-induced material flows that alter the stoichiometry of the BGCCs and ecosystems. Thus, to manage human-induced environmental degradation it is required that humans monitor and manage the BGCCs and, most importantly, the human-induced material flows that disturb the BGCCs.

The management of element cycles — i.e. of the biogeochemical cycles — has two complementary facets. First, to understand how materials are transformed and mobilised through the Earth System, by building knowledge on the current reservoir concentrations and flow rates, and on the dynamics of the Earth System, including its reaction to disturbances. Second, to understand how material are transformed and mobilised through the Economic System, since according to Melillo et al. (2003, chap. 3): "Human activity not only causes new disturbances and disturbances that mimic and/or modify the effects of natural disturbances, but it also alters the frequency, intensity and duration of "natural" disturbances [...]".

This thesis is interested in the latter and, thus, focusses on the analysis of material flows mobilised and transformed by the economic system. This approach is aligned with the suggestion of Hak et al. (2007, part IV), the 67$^{\text{th}}$ monograph of SCOPE, the Scientific Committee on Problems of the Environment, which proposes to use physical indicators to trace the impact of human activity on the Earth System and assess the sustainability of Human–Earth System interactions. In the following section, it is investigated how the economic system mobilises and transforms material flows to determine the type of analysis required to mitigate human-induced environmental degradation.

2.3 The role of the physical structure of economic activity in inducing environmental degradation

2.3.1 Taxonomy of human-induced material flows

Hereafter, the taxonomy related to the human-induced material flows defined below will be adopted in this thesis unless otherwise stated. The definitions follow the Material Flow Analysis (MFA) guidelines (Brunner and Rechberger, 2004):

Substance Any chemical element or compound composed of uniform units, thus characterized by a unique and identical constitution, i.e. homogeneous. If the unit is an atom, then the substance is a pure element of the periodic table (e.g. nitrogen or carbon); if the unit is a molecule, the substance is a chemical compound (e.g. oxygen or carbon dioxide).

Goods or products Any merchandise or ware made of one or several substances, even if used — i.e. waste.

Material Umbrella word referring to both substances and goods.

Process Transformation, transport, or storage of materials. A process can be biological: e.g. a human transforming food (a good made of several substances (hydrocarbons, proteins and lipids)) into other substances (e.g. water and carbon dioxide); or can be industrial: e.g. transportation, storage of coal, and its transformation into carbon and sulphur dioxide emissions through combustion.

Flow Ratio of mass per time (e.g. in $\mathrm{kg\,s^{-1}}$ or $\mathrm{t\,year^{-1}}$) that flows through a conductor (e.g. pipe), process (e.g. combustion) or medium (e.g. atmosphere).

System Spacial and temporal definition of the elements (either compartments or media) under study and their relationships.

Stock Amount of a material within a compartment or medium (e.g. the amount of coal in a power plant).

Stock-in-use (SiU) Amount of materials being used but not being processed, e.g. (final) goods such as cars and buildings; consumables (e.g. food or paper) are not considered stock-in-use since they are processed as they are used, i.e. transformed into its waste form.

Disposal to nature Material released from the economic system to the environment for non-productive purposes (e.g. pollutant and non-pollutant emissions and waste).

2.3.2 Disturbances due to human-induced material flows

The economic system interacts with the Earth System by extracting resources and releasing emissions. These are human-induced material flows and can disturb the Earth System since they alter the natural mobilisation and transformation rates of the associated BGCCs.

However, extracting or releasing substances to the BGCCs does not systematically disturb the Earth System. The BGCC and ecosystems can absorb changes in their composition because natural processes can compensate for some variation of material flows through homeostatic mechanisms; this constitutes the *stability* concept. In fact, the Earth System has been relatively stable. According to MacCracken and Perry (2002, p. xii): “Since the dawn of life, the planet’s environment has remained within a range of conditions that has supported life”. The concept of *stability* has evolved into the concept of *resilience* when applied to ecosystems. Resilience has been defined in two different ways (Mooney and Canadell, 2002, p. 530): as *engineering resilience* and *ecological resilience*. The former considers that ecosystems are close to a stable steady-state and, thus, resilience is defined as the ability of the ecosystem to return to that steady-state following a disturbance (Holling, 1973). The latter views ecosystems as evolving systems where disturbances can bring the system into a different regime or state, i.e. into another stability domain and, thus, focusses on how much disturbance can be absorbed before the regime changes (Walker et al., 1981).

The concept of stability or resilience has been operationalised to monitor human-induced disturbances of the BGCC and ecosystems. The concept of *critical load* has been initially developed to quantify the impact of acidifying deposition on soils, i.e. to characterise how the disturbed sulphur cycle affects a given ecosystem, but has also been applied to other environmental impacts such as eutrophication and ozone depletion (Hettelingh et al., 2001). The *critical load* of an ecosystem is: “A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson and Grennfelt, 1988). In other words, the concept of critical load means that critical thresholds exist above which ecosystem degradation occurs. The critical load can also be used to determine the threshold for a specific substance taking into consideration the interaction with other substances and pollutants and its different types of impact (Hettelingh et al., 2001). Using this method, critical thresholds for several pollutants and environmental impacts (e.g. acidification, eutrophication and ozone depletion) were calculated to inform environmental policymaking (Posch et al., 1995; Hettelingh et al., 2001). Also, critical thresholds have been identified for resource extraction (e.g. maximum number of fish catch (Funk and Rowell, 1995)).

So, the economic system extracts and releases several types of material flows, potentially disturbing the Earth System if exceeding critical thresholds. So, to mitigate environmental degradation, the extraction and emissions of materials by humans needs to be managed (i.e. reduced or redirected) not to exceed the critical thresholds of the BGCCs. To manage human-induced material flows, it needs to be understood what drives them and how. In section 2.3.3, the economic system is examined from a material flow perspective to provide some insights into these aspects.

2.3.3 On the structure and function of the economic system

Different fields have provided insights on the structure and function of human-induced material flows, i.e. why are materials required by Humans, and how are these materials managed. Industrial Ecology refers to the physical structure and function of the industrial system as "Industrial Metabolism" (Ayres, 1994a; Tukker et al., 1997; Janssen et al., 2001). However, this concept has been widened to include all human-induced material flows, e.g. the "anthropospheric metabolism" (Baccini and Brunner, 1991) or the "physical metabolism of the economy" (Krausmann et al., 2008, 2009; Steinberger et al., 2010) or even include its social aspects using the "Social Metabolism" concept (Fischer-Kowalski and Hüttler, 1998; Martinez-Alier et al., 2010). The field of Ecology has also studied the structure and function of the economic system (Odum, 1971; Beyers and Odum, 1993).

The main functions of the human-induced material flows are to nourish, to clean, to reside and work, to transport and to communicate (Brunner and Rechberger, 2004), which usually overlap with the sectoral division of the economy. However, this functional division is not useful to determine the environmental impact associated to the material flows, because it is not the function of the material that determines the impact but its composition and to which BGCC it is related. Since it is the structure of the economic system that determines which materials are extracted, from where and how, this research is interested in the structure rather than in the function of the human-induced material flows[4].

The structure of the economic system can be summarised in four main activities responsible for all human-induced material flows: agriculture, industry, household (and government) consumption and waste management (Baccini and Brunner, 1991). The central element is household consumption since part of economic activity is directly induced to produce goods and services for household consumption, and the other part produces intermediate goods and services consumed by companies, in turn producing goods and services for household consumption.

From an accounting perspective, the economic system structure is divided between production, either of intermediate or final goods, including extraction, production, manufacturing, agriculture, construction and consumption, which includes household, private and public purchase of final goods. This operative separation has led most environmental studies to allocate the impacts either to production or to consumption, developing several allocation recipes (Lenzen et al., 2007; Rodrigues and Domingos, 2008; Lenzen and Murray, 2010; Serrano and Dietzenbacher, 2010; Marques et al., 2012).

However, production and consumption of an economic system are intimately linked by design and structure and, thus, it might be misleading to analyse them separately. Products are consumed in a specific manner because they are produced in a specific

[4]Chapter 4 analyses the structure and function of dissipative systems in which case the function refers to the role that the material flow has in sustaining the structure, not the function provided to humans: e.g. a material flows might cycle through the economy being transformed several times, each having a different function from the human perspective but a single function from a system perceptive.

manner and, more importantly, they are disposed in a specific manner because they are produced in a specific manner. E.g. electronic devices are produced with the aim of minimising assembly costs, volume and weight while maximising its performance, resulting in compact devices requiring laborious disassembly and embedding numerous substances (Yamane et al., 2011; UNEP, 2013b), up to 41 in a single mobile phone (Hagelüken, 2010). Such material composition and design enhances the performance of electronic devices at the expense of making them difficult to recycle (Chancerel et al., 2009; Hagelüken and Corti, 2010; Yamane et al., 2011; UNEP, 2013b). So, the responsibility to recycle any product, i.e. to manage the material flows associated to that product, falls onto the system designing, producing and using the product, i.e. the interaction between producers and consumers. Thus, allocating the responsibility to part of the system truncates the analysis and masks possible solutions.

The linkage between the production, consumption and disposal stages applies to any product since a change of design either in terms of material content or assembly methods has consequences throughout the whole life-cycle of the product (Hauschild et al., 1997; Gaustad et al., 2010; UNEP and TU-Delft, 2010). The relevance of this linkage is revealed by "product-centric" approaches (UNEP, 2013a) implemented through the Life Cycle Analysis (LCA) of products, i.e. including the production and consumption processes (Gasafi et al., 2003; Hauschild et al., 2005; Heijungs et al., 2010). So, instead of studying the production or consumption processes as separate parts of the economic system, they can be conceptualised together as the *production-consumption structure*.

The current *production-consumption structure* is linear despite the several interactions between its four main components and sub-components because most of the flows entering the economic system exit it. The biomass extracted from the environment (e.g. wood, food and cattle) is either used for food, paper, packaging, furniture or construction purposes, being eventually disposed back to the environment as either gaseous, solid or liquid emissions (e.g. food is metabolically transformed and restored to the environment as water vapour and carbon dioxide, or as liquid emissions in sewage), in its waste form (e.g. landfilled packaging), or processed further after use (e.g. energy recovery from construction wood). In all cases, biomass inflows become outflows even if recycling occurs because biomass recycling degrades the material, leading to eventual disposal after a few cycles (e.g. paper recycling). Similarly, materials extracted from the environment have a similar fate: construction materials are used for building and are eventually disposed of after demolishing, all fossil fuels are systematically emitted to the environment after being used either for energy or material purposes[5], household chemicals are systematically

[5]Some thermo-plastics can theoretically undergo several recycling cycles but this is not the common practice (Rochat et al., 2013).

disposed to the water streams, and most goods are landfilled[6].

However, a few materials are "trapped" within the *production-consumption structure* in a cyclic manner, i.e. not participating in the mainstream linear flow. These materials are mainly metals because metals can be recycled without loosing their original properties — also called "functional recycling" (UNEP, 2011b), theoretically enabling infinite recycling[7] — and the infrastructure and activities required for that recycling have been integrated in the production-consumption structure. Although some recycling rates are relatively high for certain metals (a recovery rate above 50% has been estimated for eighteen of the sixty metals (Graedel et al., 2011; UNEP, 2011b, 2013b)), the low recycling rates of the others imply that metals still generally follow the linear path through the production-consumption structure.

Globally, human-induced material flow mobilisation and transformation has doubled per capita since the beginning of the century (Krausmann et al., 2009), increasing eight times the absolute value of materials extracted and transformed by the economic system (c.f. figure 1.1). Since the production-consumption structure is linear, the materials flows extracted are returned, *restored* hereafter, to the environment in one form or another. This statement is confirmed by the direct, linear relationship between the use of the materials and the corresponding emissions, which is calculated from the mass or energy balance. E.g. the gaseous emissions related to the combustion of fossil fuels are linearly related to the use of fossil fuels, as suggested by the concept of emission factors, which establish a linear relationship between different technologies and the type of emissions they generate (IPCC, 2006, chap. 2), or by the emission trends themselves, whose shape follow the associated resource consumption trends seen in figure 1.1. Consequently, due to the linear production-consumption structure, the increased trend of extraction and use leads to the same trend regarding the waste generated and the emissions released[8].

Thus, due to the linear structure, more resources were extracted to satisfy the increasing demand of final goods, releasing in turn more emissions. To have an idea of consequences of human activity, Ellis et al. (2010) mapped the human-induced biome (ecosystem type) transformation. They found that "between 1700 and 2000, the terrestrial biosphere

[6] Some industrialised countries are applying landfill bans although this still not the common practice at world level (UNEP, 2010b). Additionally, landfill bans does not systematically imply that the linear structure is altered. For example, waste diverted from landfills but going into incinerators either becomes gaseous emissions being released to the atmosphere and contributing to the linear structure or, become slag that is landfilled, also contributing to the linear structure.

[7] In practice, dissipative losses impede yielding a 100% recycling rate, although many losses can be minimised to achieve high recycling rates; recovery rates up to 90% are already achieved for some products (UNEP, 2013b, Table 5).

[8] Some pollutants have been curved down in some countries for some technologies (e.g. sulphur emissions from coal combustion) but these are exceptional cases. However, such reductions hide the fact that pollutants are diverted, not avoided (e.g. airborne sulphur emissions are trapped and landfilled). In general, emissions have increased as economic activity and resource consumption have grown (Caviglia-Harris et al., 2009; UNEP, 2012).

made the critical transition from mostly wild to mostly anthropogenic, passing the 50% mark early in the 20th century". Human-induced material flows and human-induced biome transformation are linked since part of the biome transformation is induced by disturbances due to the extraction of materials (either renewable or non-renewable resources) and another part is due to the environmental impacts induced by the emissions released. Rockstrom et al. (2009) quantified the global consequences of human activity and concluded that the planetary boundaries regarding climate change, biodiversity loss and the nitrogen cycle had been surpassed.

To sum up, the solution to manage human-induced material flows must be systemic. Boulding (1966) already argued that a fundamental change in the structure of human activity is required to avoid degrading the Earth System. After analysing the interaction between the economic and Earth System, he named the current linear physical and technological structure of the economic system as the "Cowboy Economy" and called for a transition towards an integrated approach that accounts for the physical limits of the Earth System. He called such ideal structure the "Spaceship Economy" to convey metaphorically the notion of the physical boundaries of the Earth. He argued that a structural change was required to achieve a sustainable "Spaceship Economy" whereby wastes would be used as resources and in combination with the natural cycles of the Earth System (i.e. the BGCCs). But what determines the material flow structure? And how can it be changed? The next section examines these questions.

2.3.4 Relationship between the techno-structure and the physical structure

The linkages between production and consumption processes imply that the technologies used in the production-consumption structure shape the structure of material flows, constituting the *techno-structure*. Products follow specific material paths (e.g. they are disposed into landfills (linear) or are recycled (circular[9])) because they are produced in a specific manner, i.e. with technologies requiring a specific combination of materials and ease of disassembly, shaping the way in which they are used, disposed and eventually recycled. In other words, technologies shape the structure of material flows within the economic system not only by themselves but by how they are linked to each other. So, modifying the physical structure of the economy, i.e. modifying the material flows constituting the physical structure, requires technological change within sectors and/or developing new sectors with new technologies: e.g., change the production technologies of current electronic devices so that they can be fully recycled and create the recycling

[9] Recycling implies a cyclic structure but its flows might ultimately be linear, since most recycling processes degrade the material flow, preventing further recycling.

industry able to manage the new recyclable waste stream. Thus, the techno-structure and physical structure are tightly linked, the techno-structure determining the physical structure.

Scientific reports suggest that technological change and improved process efficiencies might lower the human-induced environmental impacts by reducing resource extraction and emission generation (IPCC, 2007b; IEA, 2011). However, the trends of resource extraction revealed by figure 1.1 and consequent emissions generation due to the linear production-consumption structure implies that such efforts will not necessarily have the intended effect. In fact, several fold gains in resource efficiency and technological progress had already been achieved during this last century and yet the resource consumption doubled per capita. E.g., regarding energy use:

- thermal efficiency of energy converters increased steeply during this last century :
  - from about 3.5% in early combustion engines (Starr, 1971) to 43% for current electronically controlled high-speed diesel engine models or about 35% in gasoline engines (Zumerchik, 2001, pg. 333, 562);
  - from 5% in early power plants (Starr, 1971) to current 60% in combined cycle power-plants;
- aircraft drag coefficient has been reduced threefold, leading to an energy requirement reduction of the same proportion (Zumerchik, 2001, pg. 14);
- between 1974 and 2001, refrigerator energy use dropped 75% despite the fact that average volume grew 11% in the USA (Zumerchik, 2001, pg. 372);
- according to Zumerchik (2001, pg. 749), between 1973 and 1994, the energy reductions per tonne of material use were:
  - 16.7% for iron and steel,
  - 23.9% for pulp and paper,
  - 26% for cement,
  - 8% for primary aluminium, and
  - 27.4% for petroleum refining.

Similar efficiency gains were achieved in material use:

- the recovery rate of copper ore mining rose from 61% to 95% from the beginning of the century despite declining ore purity rates (Ayres et al., 2003, pg. 15);
- a reduction in 11.2% in the materials required to produce a vehicle from 1978 to 1988 (Herman et al., 1990, table 3);
- a 225% yield increase in the agricultural sector during this last century (in kg/ha) although with a 100% increase in fertiliser use between 1960–1995 (Koning et al., 2008).

- 55% increase in world paper recycling between 1970–1997 (van Beukering and Bouman, 2001).

The "rebound effect" or Jevons' Paradox (Jevons, 1865) explains partially why these innovations have not curbed resource extraction or emissions. The rebound effect is caused by a technological improvement affecting the resource extraction, use or emission efficiency which leads to increased use of the resource because (some of) its side-effects have been mitigated and/or its price reduced. Jevons observed that the efficiency gains in the transformation of coal into work (power) led to increased consumption of the resource (by making it relatively cheaper) instead of reducing its consumption due to the efficiency gains. Similar behaviours have been noticed regarding many other technologies: vehicle fuel consumption (Binswanger, 2001), residential energy for heating, cooling and lighting (Greening et al., 2000), and ore extraction and refining (Ayres et al., 2003).

The other explanation for the fact that technological change may be unable to curb resource extraction and emissions is that technological change is heavily conditioned by current technologies, infrastructure and other variables — known as the "selective environment" for a given technology (Kemp and Soete, 1992). The "selective environment" implies that technological change favours existing technologies over new (cleaner) technologies because they have comparative advantages (returns to scale, favourable institutional framework, customer acceptance, etc.). Consequently, incremental technological change reinforces the existing technologies and the linkage between them (Nemet, 2009). Thus, the current linear physical structure of economies is maintained despite (incremental) technological innovation. As noted by Ehrenfeld (2013), "almost everything being done in the name of sustainability entails attempts to reduce unsustainability. But reducing unsustainability, although critical, does not and will not create sustainability". This statement also captures the logic of incremental technological change: improving current technologies is important (e.g. to reduce emissions, i.e. "reducing unsustainability") but does not lead to a system where emissions do not disturb the Earth system (i.e. do not "create sustainability").

Fortunately, according to Evolutionary Theory, by using specific combinations of policy instruments, technological evolution might be "guided" (Menanteau et al., 2003; Buen, 2006; Nemet, 2009; Furtado et al., 2011; Olmos et al., 2012), but this requires a technological road map to induce technological change in the desired direction (Taylor, 2008). The issue becomes then: towards which technological structure should the economic system be guided? So, ideally, to guide technological change, a sustainable technological structure of the economic system should be characterised beforehand or, at least, the structural features that are to be improved to reduce systemically the environmental impact associated to human-induced material flows.

However, from an environmental perspective, it is not the technological structure that matters but the physical structure that the technological structure determines, because what affects the environment is the type and quantity of material flows that are extracted from the environment and released back to it. So, in fact, a technological transition towards a more resource efficient economic system relies on the analysis of the underlying material flows of the economic system, i.e. of its physical structure. Thus, hereafter, the physical structure of the economic system will be the focus of the study and used to inform technological developments. For example, if the analysis of the physical structure indicates that a specific material flow should be recycled, the associated technological changes can be identified and incentivise the recycling sector and associated technologies with the policy mixes described in the previous paragraph. Similarly, if a material flow is to be mitigated, the production technologies related to that material flow can be identified and altered to reduce the need of that material flow (as it has already happened with some materials such as CFCs and asbestos).

The search for the relevant (physical) structural features to mitigate environmental degradation systemically has two different aspects. First, it is required to characterise the structure itself, i.e. to find the representation or modelling framework that allows the researcher to analyse the system at the relevant level of analysis. Section 2.2 revealed that human-induced environmental degradation is fundamentally due to human-induced disturbances of the BGCCs induced by the material flows mobilised and transformed during production and consumption; consequently, a material level analysis is required to link environmental degradation to human activity. Thus, the modelling frameworks and indicators for human-induced material flows are reviewed in section 2.4 to identify the modelling or accounting framework to be used for analysis. Second, the key structural features (or ideal structure) to mitigate environmental degradation are to be identified. So, in section 2.5, the theories and methods that have been suggested to mitigate environmental degradation are reviewed.

For completeness, the main characteristics of current scientific assessments integrating both aspects are reviewed below.

Current plans and strategies to shape the physical structure of the economies are limited in scope, hampering the potential to provide a comprehensive solution to avoid environmental degradation. The few comprehensive technical reports have a short assessment time-span: from 30 to 100 years (IPCC, 2007b; IEA, 2011; IPCC, 2014b) . The biggest international effort aiming to provide insights on current and future Human–Earth System interactions — the report series provided by the IPCC (IPCC, 1990, 1996, 2001, 2007c, 2014b) — only cover very specific material flows, closely related to GHG emissions, and for a relatively short period of time (hundred years), which can be considered at most a mid-term approach when considering the time required to develop new technologies and substitute the old ones. Technological reports of smaller size (IEA, 2011) have more limited time-spans, which provide misleading guiding instruments for technological development since they induce the "lock-in" of the suggested technologies (Unruh and Carrillo-Hermosilla, 2006). For example, the International Energy Agency (IEA, 2011) has developed future technological scenarios, none considering a full switch towards renewable energy sources, ignoring the feasibility studies of such technological transition (Jacobson and Delucchi, 2011; Delucchi and Jacobson, 2011). Consequently, the technological system developed following the IEA strategies might in the best case delay (and in the worst lock) the future switch towards a renewable energy system because other technologies have been favoured earlier in time.

Also, due to the limited time and natural resources assessment approach of these reports, future key issues associated to the implementation of the selected technological strategies might go unnoticed. The IPCC (2014b) and IEA (2011) suggest a new set of technologies which improve (at least partially) the current situation in the considered time-span; however, they are not comprehensive enough to assess whether the suggested solutions can be developed at the scale required. For example, switching to renewable energy sources and electric vehicles will require new material extraction to implement the required infrastructure. In particular, the copper content per capita will increase significantly due to new technological requirements and, in that case, Gordon et al. (2006) warn that copper might become scarce by the end of the century, jeopardising the implementation of the selected technological option. Similarly, other materials might pose a threat to human development if they are not taken into account in the strategic long-term development of new technologies and material flow management. For example, the availability of phosphorus might become an issue at the end of the century since it is a basic, non-substitutable nutrient for agriculture (Carpenter and Bennett, 2011; Cordell et al., 2009). Thus, managing the material flows required by the economic system and integrating this management in its technological development and evolution is vital to guarantee the long-term planning of technological development. In this sense, the research developed in this thesis is also relevant, since it will enable researchers to assess the resource requirements and emission generation of new technological regimes or structures through the analysis of the physical structure.

The IPCC (2014b) states that technology policy complements other mitigation policies. However, it is the nature of the technologies in use that determines the type and amount of material flows mobilised and transformed by the economic system, in turn determining the environmental degradation of the Earth System. Since it is the technological structure of production and consumption — the techno-structure — that determines the resource requirements and emissions generation of the economic system — i.e. the physical structure

—, and this structure can only be selectively changed through guided technological change, the focus of policy making should be inverted, with technology policy as the central driver to mitigate environmental degradation. Other mitigation policies can help mitigating the effects of an ill-shaped techno-structure (e.g. inducing behavioural changes) but cannot alter what is fundamentally shaping the mobilisation and transformation of human-induced material flows, the structure itself. The methods developed in this research are also relevant in this matter, since they can be used to inform environmental and industrial policies to alter the technological structure of the economic system to lower its environmental impact through the analysis of its physical structure.

2.4 Modelling and quantifying human-induced and Earth System material flows

2.4.1 Earth System modelling

Earth System Science has developed the theoretical knowledge to model the Earth System material flow mobilisation and transformation (Butcher, 1992; Bethke, 2007; Sigel et al., 2005) simultaneously with the experimental knowledge to measure the material flows associated to the different BGCCs (e.g. measuring buoys for ocean monitoring (Mills et al., 2003) or stratospheric globes for atmosphere monitoring (Ehhalt, 1974)). The modelling challenge is great due to the number of substances present in the Earth System and the dynamic, non-linear, feed-back interaction between simultaneous processes within given geospheres and between the different geospheres. However, Earth System Science is able to explain the phenomena observable in the Earth System (e.g. ocean acidification, climate change, eutrophication, changes in ecosystems) and has been the main field providing information to address global issues related to Earth System dynamics (e.g. climate change) (IPCC, 2007c, 2013).

Unfortunately, the Earth System Sciences knowledge on material flow modelling cannot be ported to assess the physical structure of the economic system because the drivers underpinning the mobilisation and transformation of material flows in the Earth System differ from the human-induced ones. In particular, the driving force behind material mobilisation and transformation within the Earth System is substance concentration (Butcher, 1992, chap. 4) (e.g. the amount of carbon dioxide absorbed by oceans depends on the atmospheric carbon dioxide concentration), while the driving force underlying human-induced material mobilisation and transformation is the production of goods and services. Additionally, once driven by humans, the human-induced materials flows are directly related to other human-induced material flows (e.g. the amount of carbon dioxide emissions depend on the amount of ancillary substances mobilised and transformed (e.g. biomass or fossil fuels)), implying a different modelling approach based on flows and not on stocks (and flows) as in the Earth System case. Although it is not impossible to harmonise both modelling approaches, it implies that the theoretical tools developed by Earth System Sciences cannot be ported in a straight forward manner to analyse the anthropogenic metabolism. To fill this gap, Integrated Assessment Models (IAM) — models combining sub-models from different fields and using different modelling approaches — have been developed to couple the economic system to the Earth System; they are reviewed in section 2.4.3.

2.4.2 Accounting and modelling frameworks representing the material flows associated to economic activity

2.4.2.1 Input-Output Analysis

Input-Output Analysis is a modelling framework that enables researchers to calculate endogenously the primary inputs (imports, value added factors such as wages, profits and taxes) and intermediate production required by the whole economy to satisfy a given final demand — the only exogenous component. It was originally developed to analyse economic transactions but it has been further developed to account for the material flows underlying economic activity. The idea of systemic interconnection between the economic sectors dates back to the end of the XVI$^{\text{th}}$ century (Petty, 1690) and was first rudimentarily formalised by Quesnay (1759). However, it was not until 1941 that a paired accounting and modelling framework would be developed to account for the indirect effects associated to the inter-sectoral relationships Leontief (1941). This framework is known as Input-Output Analysis and relies on compiling the data representing the economic activity as Input-Output Tables (IOTs) and using Input-Output models to analyse it.

Monetary Input-Output Tables and associated model The first types of IOTs to be developed were Monetary IOTs, also known as MIOTs (Leontief, 1941), which aims to represent the production system transactions within the economy. MIOTs entail primary inputs (e.g. value added factors such as wages, profits and taxes) represented by a primary inputs vector $\mathbf{v}'$, the inter-sectoral exchanges (also known as intermediate production or demand) represented by the inter-sectoral matrix $\mathbf{Z}$, and final production, which can be classified as either household, governmental or entrepreneurial consumption[10], represented by final output vector $\mathbf{f}$. Imports and Exports can also be included in several manners; a

[10]"Entrepreneurial" consumption is usually known as *gross capital formation*.

typical way is to consider imports as primary inputs and exports as final demand. The total outputs of each sector (i.e. the column sum of each row representing a sector) equals the total inputs of each sector (i.e. the row sum of each column representing a sector); thus, total outputs and inputs are the same and are represented by the total outputs (or inputs) vector $\mathbf{x}$. This is due to the double entry bookkeeping account relationship where the debits of each sector must equal its credits. An n sectors MIOT is represented in table 2.1.

	Sector 1 ... Sector n	Final demand	Total outputs
Sector 1 ⋮ Sector n	$\mathbf{Z}$	$\mathbf{f}$	$\mathbf{x}$
Value added	$\mathbf{v}'$		
Total inputs	$\mathbf{x}'$		

TABLE 2.1: Monetary Input-Output Table with n sectors.

Then, Leontief (1941) used certain assumptions to reduce all inter-sectoral interactions to a systems of linear equations, which could in turn be solved using linear algebra. The starting point is the accounting relationship: intermediate production plus final production equals total production:

$$\mathbf{Z} \cdot \mathbf{i} + \mathbf{f} = \mathbf{x} \tag{2.1}$$

Then Leontief used the key assumption that intermediate production is proportional (i.e. linearly related) to total production by means of a technical coefficient matrix $\mathbf{A}$:

$$\mathbf{Z} = \mathbf{A} \cdot \hat{\mathbf{x}} \Leftrightarrow \mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \tag{2.2}$$

Substituting equation 2.2 in equation 2.1 enables researchers to relate final production to total production:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{f} \tag{2.3}$$

where

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{2.4}$$

is known as the Leontief inverse matrix.

However, at this point only total values of the transactions are know, so it is unknown the prices and quantities associated to these transactions. Therefore, Leontief used a mathematical "trick": he first considered that each sector produces homogeneous products (if not, the sector could in theory be disaggregated till this assumption holds) and, then, he considered the same unitary prices for the quantity of goods that are actually produced. This enables researchers to considers the previous equation as quantities. Hence, the model hereby developed in known as the *quantity output-driven model*, also known as the Leontief model.

IOA is a powerful analytical tool because it is able to capture not only the direct effects associated to the production of final products but also the indirect effects. Understanding and quantifying indirect effects is key because these effects might even outweigh direct effects. The direct effects can be understood as the direct requirements to produce a specific good (e.g. the labour and materials required by the sector producing the final good), and the indirect effects are the indirect requirements, i.e. the labour and materials required the rest of the economy to produce the materials required by the sector producing the final good. So, indirect effects also include feedback effects (i.e. cycling intersectoral interactions), since sector A might require an intermediate good from sector B which in turns requires an intermediate good from sector A. In input-output terms, the direct effects and relationships are contained within the technical coefficient matrix ($\mathbf{A}$) and the indirect effects and relationships within the Leontief inverse matrix ($\mathbf{L}$).

The Leontief model has been extensively used to model how the economy — i.e. all economic sectors — would (directly and indirectly) respond to changes in its final demand composition. I.e., it enables researchers to estimate the economy-wide increase or decrease of any factor represented in the MIOT (e.g.: wages, jobs, GDP) related to the increase or reduction of the activity of selected sectors. To facilitate this type of analysis, IOA has developed the multiplier analysis, which enables researchers to identify which sectors are inducing most indirect effects without requiring to calculate the impact of a change in each final demand component independently, only the multipliers are calculated (Miller and Blair, 2009). For example, the simplest multiplier is the production multiplier ($\mathbf{m}^{prod}$), conveying the production induced economy-wide to generate one unit of each final good. It is calculated as

$$\mathbf{m}^{prod} = \mathbf{i}' \cdot \mathbf{L} \tag{2.5}$$

Also, income, employment, value added multipliers can be developed (Miller and Blair, 2009, chap. 6).

Another approach to analyse MIOTs is to try how each sector is linked to the rest of the economy; this approach is called linkage analysis. The most basic analytical tools are the backward and forward linkage analyses, which can in turn be applied to find the direct and total linkages. For example, the direct backward linkage measures represent how much each sector relies on intermediate production (i.e. on the production of the rest of the economy). It was first suggested by Chenery and Watanabe (1958) as follows:

$$\mathbf{b}^{direct} = \mathbf{i}' \cdot \mathbf{A} \tag{2.6}$$

The total backward linkage measures are calculates as the total output multipliers; according to (Rasmussen, 1957):

$$\mathbf{b}^{total} = \mathbf{i}' \cdot \mathbf{L} \tag{2.7}$$

In this case, can be interpreted as the total production induced (upstream) to produce a unit of each final good. An broad literature exists on variations of these measures and on methods to combine backward an forward linkages (see Miller and Blair (2009, chap. 12.2) for a review).

Also, IOA can be used to examine whether it is final demand or technological change that is altering the economic structure; this is studied using the Structural Decomposition Analysis. The idea is to compare the structure of the economy at two points in time, each represented by a superscript t_0 or t_1. So, using equation 2.3,

$$\mathbf{x}^{t_0} = \mathbf{L}^{t_0} \cdot \mathbf{f}^{t_0} \tag{2.8}$$

$$\mathbf{x}^{t_1} = \mathbf{L}^{t_1} \cdot \mathbf{f}^{t_1} \tag{2.9}$$

Then, the variation is gross outputs through in the period under study is:

$$\Delta\mathbf{x} = \mathbf{x}^{t_1} - \mathbf{x}^{t_0} \tag{2.10}$$

$$= \mathbf{L}^{t_1} \cdot \mathbf{f}^{t_1} - \mathbf{L}^{t_0} \cdot \mathbf{f}^{t_0} \tag{2.11}$$

Equation 2.10 can be rearranged in a number of forms (Miller and Blair, 2009, chap. 13.1); e.g. replacing $\mathbf{L}^{t_0}$ with $(\mathbf{L}^{t_1} - \Delta\mathbf{L})$ and $\mathbf{f}^{t_1}$ with $(\mathbf{f}^{t_0} + \Delta\mathbf{f})$:

$$\Delta\mathbf{x} = \mathbf{L}^{t_1} \cdot (\mathbf{f}^{t_0} + \Delta\mathbf{f}) - (\mathbf{L}^{t_1} - \Delta\mathbf{L}) \cdot \mathbf{f}^{t_0} \tag{2.12}$$

$$= \Delta\mathbf{L} \cdot \mathbf{f}^{t_0} + \mathbf{L}^{t_1} \cdot \Delta\mathbf{f} \tag{2.13}$$

Equation 2.13 constitutes a decomposition of the change of total outputs between the first term, which represents the structural change due to technological change, and the second term, which represents the structural change due to the change in final demand. A broader discussion of this literature can be found in Rose and Casler (1996) or Dietzenbacher and Los (1998). Such approach can be used to study different types of issues: e.g. economic (Skolka, 1989) or energy and environmental (Wachsmann et al., 2009).

The Leontief model can be extended to explore the relationships between different economies, either by using Interregional or Multiregional models (Miller and Blair, 2009, chap. 3). These types of models follow the same exact structure of the MIOT presented previously; the only difference is that some sectors belong to one country and others to another. There is no theoretical limit to the amount of sectors nor countries that can be represented in Interregional or Multiregional IOTs; however, their size might complicate their operation and analysis. The analysis that can be applied on these tables are the same ones that can be applied to conventional MIOTs.

The Leontief pollution abatement model and associate tables Leontief (1970) also developed the first Input-Output model aiming to explore the environmental impact of the economy: the pollution abatement model. Leontief wanted to explore how much would cost to treat certain emissions and include this cost within the model in an endogenous manner. For this, he expanded the MIOT by adding an extra row indicating the amount of emissions generated by each sector and an extra column corresponding to the sector mitigating the emissions. m emissions can be accounted for by including m extra rows (noted $\mathbf{w}'$) and the corresponding m extra columns ($\mathbf{p}$) (Leontief and Ford, 1972). The extra rows represent the emissions generated by each sector in physical terms, i.e. in physical units, including the emission generation by the new pollution abatement sectors ($\mathbf{w}'_p$). The new abatement sectors exchange monetary flows with the rest of the economy as if they were normal sectors. Thus, the extra rows and columns constitute, together with the intersectoral matrix, a new augmented inter-sectoral matrix. An IOT that can be used with the pollution abatement model is presented in table 2.2.

	Sector 1	...	Sector n	Abat. sectors	Final demand	Total outputs
Sector 1						
⋮		$\mathbf{Z}$		$\mathbf{p}$	$\mathbf{f}$	$\mathbf{x}$
Sector n						
Emissions		$\mathbf{w}'$		$\mathbf{w}'_p$	$\mathbf{f}_w$	
Value added			$\mathbf{v}'$			

TABLE 2.2: Monetary Input-Output Table with n sectors and m pollution abatement sectors.

This augmented inter-sectoral matrix can be operated with the conventional (quantity, output-driven) Leontief model even if the emission rows are in physical terms. The are two differences with the conventional model which affect the interpretation of the results rather than its operation. The first difference is that the final production of each of the emission rows ($\mathbf{f}_w$) represent the maximal amount of emissions that the system is allowed to emit, i.e. represents the emission threshold tolerated for each emission. Therefore, the "final demand" defines the level of activity of the abatement sectors. In other words, the model will endogenously calculate the level of activity of the pollution abatement sectors to mitigate the emissions to the threshold previously defined. The second difference is that total outputs do not equal total inputs since part of the inter-sectoral matrix is in physical units; in this case, only the total outputs ($\mathbf{x}$) can be used to operate the model.

This model was first proposed in Leontief (1970) and has been developed further by Qayum (1991) and Luptacik and Böhm (1994, 1999). The extension to several pollution types is covered in Ayres and Kneese (1969), Gutmanis (1975), and Leontief and Ford (1972).

The original idea of Leontief (1970) was to endogenise the "negative externality" and consider the generation and elimination of pollutants as an integral part of the economic process. However, this framework has not been widely adopted, probably because it does not reflect how emissions are actually abated — usually, each sector usually deals with its own emissions, except for centralised cases such as waste water treatment —, but more importantly, because of the lack of accurate data on the abatement options (Allan et al., 2007).

Environmentally-Extended Monetary Input-Output Tables and associated models A different approach to model environmental impacts of the economic activity is to extend the MIOT framework to account for selected natural resources and emissions associated to economic activity; this constitutes the Environmentally Extended (EE-MIOT) approach. It differs from the Leontief pollution abatement model in that it does not endogenise the treatment (abatement) of the pollution generated, it simply enables researchers to calculate the total amount of selected resources and emissions associated to a given final demand. EE-MIOTs have a common MIOT at its core (as the one in table 2.1), but extended with the environmental variables to be observed, either as inputs (e.g. water, land, natural resources, energy,...) or outputs (e.g. airborne emissions such as carbon dioxide, particulate matter or sulphur, water-borne emissions such as nitrogen or phosphorus, etc.).

To build an EE-MIOT, the extended variables that represent sectoral inputs (natural resources) can be added as rows below the original MIOT and named $\mathbf{r}_i$ (one extra row per type of primary natural resource). The the extended variables that represent sectoral outputs (emissions) can be added as columns after the original MIOT and named $\mathbf{e}_i$ (one extra column per type of emissions). The extended variables are in physical units but are not necessarily the same: e.g. land requirements in square kilometres, water requirements in cubic meters and carbon dioxide emissions in tons. Since these extra variables are extensions to the MIOT, they do not contribute to the total outputs or inputs of the MIOT ($\mathbf{x}$). An environmentally-Extended MIOT is presented in table 2.3.

	Sector 1	...	Sector n	Final demand	Total outputs	Extended outputs e_1	...	e_m
Sector 1								
$\vdots$		$\mathbf{Z}$		$\mathbf{f}$	$\mathbf{x}$	$\mathbf{e}_1$	$\cdots$	$\mathbf{e}_m$
Sector n								
Value added		$\mathbf{v}'$						
Total inputs		$\mathbf{x}'$						
Extended inputs:								
r_1		$\mathbf{r}'_1$						
$\vdots$		$\vdots$						
r_k		$\mathbf{r}'_k$						

Table 2.3: Environmentally-Extended Monetary Input-Output Table with n sectors, k extended inputs and m extended outputs.

The EE-MIOT is operated by applying the Leontief (quantify, output-driven) model on the underlying MIOT; then, the extended variables are calculated using the extended coefficient approach. I.e., the original extended values are divided by the total output of the sector to obtain a sectoral resource requirements (or emission) intensity. The input coefficients associated to the extended input vector $\mathbf{r}'$ are:

$$\mathbf{c}^r = \mathbf{r}' \cdot \hat{\mathbf{x}}^{-1} \tag{2.14}$$

These intensities are used to find the new extended values after finding the total outputs associated to a new final demand. The total amount of extended inputs ($\mathbf{r}^*$) associated to a new final demand $\mathbf{f}^*$ are:

$$\mathbf{r}^* = \hat{\mathbf{c}}^r \cdot \mathbf{L} \cdot \mathbf{f}^* \tag{2.15}$$

$$= \hat{\mathbf{c}}^r \cdot \mathbf{x}^* \tag{2.16}$$

The same procedure can be applied to the extended emissions:

$$\mathbf{c}^e = \mathbf{e}' \cdot \hat{\mathbf{x}}^{-1} \tag{2.17}$$

$$\mathbf{e}^* = \hat{\mathbf{c}}^e \cdot \mathbf{L} \cdot \mathbf{f}^* \tag{2.18}$$

EE-MIOT have been broadly used to model the systemic environmental impact of economies because they are particularly well adapted to current system of national accounts. The core data is based on the (economic) system of national accounts (which are used to build the MIOT) and provides a consistent and reliable dataset to model economic activity. Then, the environmental variables are added matching the sectoral disaggregation of the MIOT. In some cases, the environmental data might already be provided following the same or very similar disaggregation, simplifying the exercise, since the system of environmental accounts have precisely been devised as satellite accounts to the economic accounts.

The underlying idea to use Environmentally Extended IOTs is to model the material flow requirements or emissions associated to economic activity. According to Sánchez-Chóliz and Duarte (2005):

> Although most of the research in this field has focused on atmospheric pollution (because of the availability of data, the global nature of the problem, which justifies the introduction of demand-side policies, and its relationship with international trade), the input-output methodology can also be adapted to the study of other environmental problems affecting land and water use, forestry and energy requirements, as well as soil and water pollution.

In particular, the main application of EE-MIOTs is to calculate the "ecological footprint" of economic activity of one or various factors described above. The underlying idea of the ecological footprint as described in Wackernagel and Rees (1996); Wackernagel et al. (2003) is to calculate the total natural resources requirements of economic activity, either used directly as inputs (e.g. agricultural land or land providing water resources) or indirectly (e.g. as land required to absorb pollutants generated by economic activity), by using a common denominator — used land — to convey the idea of the biological space used by economic activity. IOA has been used to calculate the ecological footprint as suggested by Wackernagel and Rees (1996) with some modifications of the underlying assumptions (Wiedmann et al., 2006). However, the environmental footprint of economic activity has also been calculated in a direct fashion, i.e. by providing the value of the actual use of resources without reducing the impact to the common denominator of land use. Previous studies have focussed on: fresh water requirements and waste water generation (Sánchez-Chóliz and Duarte, 2005; Guan and Hubacek, 2007; Dietzenbacher and Velazquez, 2007), carbon emissions (Sánchez-Chóliz and Duarte, 2004; Guan et al., 2008; Imori and Guilhoto, 2010; Barrett and Scott, 2012), embodied energy (Machado et al., 2001) and land use (McDonald and Patterson, 2004)).

Apart from calculating the ecological or environmental footprint, EE-MIOTs can be used to explore the cause of environmental impact or footprint using different approaches: linkage analysis (Sánchez-Chóliz and Duarte, 2005), multi-regional analysis (Guan and Hubacek, 2007; Wiedmann and Barrett, 2013), structural decomposition analysis (e.g. applied to an IPAT decomposition of the drivers of carbon dioxide emissions (Guan et al., 2008)) or by quantifying the embodied resources in final consumption (e.g. "virtual" water exported to other regions (Guan and Hubacek, 2007; Dietzenbacher and Velazquez, 2007), embodied carbon dioxide emissions (Sánchez-Chóliz and Duarte, 2004), ecological footprint (Wiedmann et al., 2006) or energy and carbon embodied in international trade (Lenzen, 1998; Machado et al., 2001)).

Hybrid Input-Output Tables and associated models Hybrid-IOA is a different type of approach because it represents the inter-sectoral flows partly in physical units and partly in monetary units — hence the hybrid prefix. It was developed after the oil crises to study the energy requirements of the economic system (Bullard and Herendeen, 1975a,b) and it is still the focus of current research since it has some advantages compared to the traditional MIOT or EE-MIOT approach. For example, by using physical units instead of the monetary ones, the flows are more accurately characterised since the price variations between sectors do not affect the physical flows (but do affect the prices, and hence the flows used in monetary units); this is the main advantage of using physical units instead of monetary ones. This is particularly true for energy flows since energy prices vary depending on who is purchasing the energy; therefore, the same flow to different sectors in monetary terms might actually be hiding a difference in the physical flow distribution between these sectors.

The hybrid-IOT has the same structure as a MIOT but containing some flows in physical units. To account for this difference, each component of a hybrid-IOT has an asterisk (*) superscript. The hybrid-IOT presented below represents the exchange between n sectors, with k industrial sectors and m energy sectors; the monetary flows are ranged in a first block of rows and the physical flows in a second block of rows. Hence, the hybrid-IOT is composed of: a primary inputs matrix $\mathbf{V}^*$, which entails the added value matrix in monetary terms $\mathbf{V}$ and the primary energy inputs matrix in physical terms $\mathbf{R}$ (most of its values are null excepts for the primary energy sectors which extract energy from the environment; the matrix has l rows, each corresponding to a different primary energy source); an inter-sectoral matrix $\mathbf{Z}^*$, which entails the monetary exchanges between sectors as $\mathbf{Z}$ and the physical exchanges as $\mathbf{H}$; and finally, the final demand $\mathbf{f}^*$ is composed of the final demand in monetary terms $\mathbf{f}$ and in physical terms $\mathbf{q}$. Table 2.4 represents a hybrid-IOT using the condensed asterisk notation and table 2.5 represents a hybrid-IOT using the notation reflecting the different units.

	Sector 1	...	Sector n	Final demand	Total outputs
Sector 1					
$\vdots$		$\mathbf{Z}^*$		$\mathbf{f}^*$	$\mathbf{x}^*$
Sector n					
Primary inputs		$\mathbf{V}^*$			

TABLE 2.4: Condensed notation of a Hybrid Input-Output Table structure with n sectors.

	Sec 1	$\cdots$	Sec k	En Sec 1	$\cdots$	En Sec m	Final demand	Tot outputs
Sector 1	z_{11}			$\cdots$		z_{1n}	f_1	x_1
$\vdots$	$\vdots$			$\ddots$		$\vdots$	$\vdots$	$\vdots$
Sector k	z_{k1}			$\cdots$		z_{kn}	f_k	x_k
Energy Sector 1	h_{11}			$\cdots$		h_{1n}	q_1	g_1
$\vdots$	$\vdots$			$\ddots$		$\vdots$	$\vdots$	$\vdots$
Energy Sector m	h_{m1}			$\cdots$		h_{mn}	q_m	g_m
Value added	v_1			$\cdots$		v_n		
Energy source 1	r_{11}			$\cdots$		r_{1n}		
$\vdots$	$\vdots$			$\ddots$		$\vdots$		
Energy source l	r_{l1}			$\cdots$		r_{ln}		

TABLE 2.5: Hybrid Input-Output Table structure with l primary energy sources and n sectors (k industrial sectors and m energy sectors). The first k rows are in monetary units and the following m rows in physical units. The value added row is in monetary units and the primary energy sources in physical units.

The Leontief model can be applied to a hybrid-IOT formulated as the one in table 2.4 (Bullard and Herendeen, 1975a; Miller and Blair, 2009) because it has the same structure as a MIOT, i.e. containing an inter-sectoral matrix, a final demand vector and a total outputs vector which is the row sum of the previous elements; therefore,

$$\mathbf{Z}^* \cdot \mathbf{i} + \mathbf{f}^* = \mathbf{x}^* \tag{2.19}$$

Then, the technical coefficient matrix can be defined as:

$$\mathbf{A}^* = \mathbf{Z}^* \cdot \hat{\mathbf{x}}^{*-1} \tag{2.20}$$

Substituting equation 2.19 in equation 2.20:

$$\mathbf{x}^* = (\mathbf{I} - \mathbf{A}^*)^{-1} \cdot \mathbf{f}^* \tag{2.21}$$

where

$$\mathbf{L}^* = (\mathbf{I} - \mathbf{A}^*)^{-1} \tag{2.22}$$

is equivalent to the Leontief inverse matrix.

The hybrid-IO model lies on the embodied energy conservation principle, as first stated in Bullard and Herendeen (1975a): in input-output terms, the embodied (output) energy of a product equals the sum of the previously embodied energy in the (intermediate) products used for its production plus the energy provided by natural resources. Note that this principle is very different from the energy (or mass) balance principle, which reveals the energy content of the output itself, excluding the energy that has been lost in the process of producing it. Then, following Bullard and Herendeen (1975a), the embodied energy conservation principle can be formalised in input-output terms as:

$$\epsilon_j \cdot x_j^* = \sum_{i=1}^{n} \epsilon_i \cdot z_{ij}^* + r_j \tag{2.23}$$

where $\boldsymbol{\epsilon}$ is the embodied energy per unit of outputs and its matrix form ($\boldsymbol{E}$) is of dimension $l \times n$ (l types of primary energy), matching the dimensions of $\mathbf{R}$. Equation 2.23 can be rewritten in matrix form as

$$\boldsymbol{E}\hat{\mathbf{x}}^* = \boldsymbol{E} \cdot \mathbf{Z}^* + \mathbf{R} \tag{2.24}$$

Using equation 2.20 in 2.24:

$$\boldsymbol{E}\hat{\mathbf{x}}^* = \boldsymbol{E} \cdot \mathbf{A}^* \cdot \hat{\mathbf{x}}^* + \mathbf{R} \tag{2.25}$$

$$\boldsymbol{E} = \mathbf{R} \cdot \hat{\mathbf{x}}^{*-1} \cdot (\mathbf{I} - \mathbf{A}^*)^{-1} \tag{2.26}$$

Using equation 2.22, equation 2.26 can be rewritten as

$$\boldsymbol{E} = \mathbf{C}^r \cdot \mathbf{L}^* \tag{2.27}$$

where $\mathbf{C}^r = \mathbf{R} \cdot \hat{\mathbf{x}}^{*-1}$ are the primary energy input coefficients (i.e. the primary energy required by each sector normalised by the total outputs); these are non-null only for the primary energy sectors. Thus, $\boldsymbol{E}$ represents the primary energy required directly and indirectly to produce each final product, i.e. its embodied energy. It is thus the total energy requirements matrix.

In this case , the amount of emissions generated by the economy can be calculated by introducing a matrix of emission coefficients $\mathbf{C}^e$ corresponding to the emissions associated to each energy source and sector. Then, the total emissions matrix $\mathbf{\Phi}$ would be

$$\mathbf{\Phi} = \mathbf{C}^e \cdot \mathbf{L}^* \tag{2.28}$$

In terms of material flows, the hybrid-IOT and model has been widely used in the analysis of different energy sources such as coal, oil, gas, etc. (Bullard and Herendeen, 1975a; Treloar, 1997; Machado et al., 2001; Lindner and Guan, 2014), but also to study the embodiment of other materials such as water (Lin, 2009) and metal ores (Nakamura et al., 2008).

The hybrid model was initially developed to study energy consumption due to the oil crises and focussed on understanding the energy costs of goods and services (Bullard and Herendeen, 1975a,b). Currently, the use of the framework has been shifting towards identifying more accurately and providing better estimates of carbon emissions (Machado et al., 2001; Lindner and Guan, 2014). Also, the framework methodology is being extended to account for the Ecological Footprint (Weinzettel et al., 2014).

Physical Input-Output Tables and associated analytical methods IOTs can also be built using physical flows exclusively and are then called Physical IOTs (PIOTs). However, two very different types of PIOTs exist: PIOTs *with* and *without* disposals to nature[11].

PIOTs *without* disposals to nature only represent the material flows that are embedded in final production, i.e. without accounting for the emissions. They have exactly the same structure as MIOTs and they are *similar* to them, i.e. they share the same algebraic properties because the only difference between a MIOT and a PIOT *without* disposals to nature is the vector of prices (Weisz and Duchin, 2006). Table 2.6 represents such table; the only difference with a MIOT is that the primary inputs are natural resources —represented by a vector $\mathbf{r}'$—, instead of the value added vector $\mathbf{v}'$.

However, a PIOT *without* disposals to nature has never been built in practice because it defeats the purpose of building a PIOT, which is to analyse the environmental impact associated to economic activity. A PIOT without disposals to nature excludes the emissions associated to production and, thus, represents only a fraction of the physical flows actually used by the economic system, thereby excluding part of the primary resources actually extracted. Therefore, PIOTs without disposals to nature cannot be used to assess the actual environmental impact of the economic system, since they cannot be used to quantify the environmental impact associated to primary resource extraction

[11] Disposals to nature can be any type of emissions, either waste, pollutant or non-pollutant outflows of the economic system.

	Sector 1	...	Sector n	Final demand	Total outputs
Sector 1					
$\vdots$		$\mathbf{Z}$		$\mathbf{f}$	$\mathbf{x}$
Sector n					
Value added		$\mathbf{r}'$			
Total inputs		$\mathbf{x}'$			

TABLE 2.6: Physical Input-Output Table without disposals to nature with n sectors. All flows are in physical units.

nor to emission generation. Hence, PIOTs without disposals to nature will not be further considered in this research.

However, PIOTs *with* disposals to nature also exist and have a different table structure because they include the emissions released by each sector. Hereafter, the term PIOT will only refer to PIOTs *with* disposals to nature. The structure of a PIOT (with disposals to nature) resembles a MIOT but it has an extra final output representing the disposals to nature. This is a key difference because it implies that each sector does not produce an homogeneous output, which is a premise to apply the Leontief (quantity, output-driven) model, as explained when examining the analysis of MIOTs. Table 2.7 represents a PIOT with disposals to nature, which are represented by a final output vector $\mathbf{w}$.

	Sector 1	...	Sector n	Final demand	Disposals	Total outputs
Sector 1						
$\vdots$		$\mathbf{Z}$		$\mathbf{f}$	$\mathbf{w}$	$\mathbf{x}$
Sector n						
Resources		$\mathbf{r}'$				
Total inputs		$\mathbf{x}'$				

TABLE 2.7: Physical Input-Output Table with disposals to nature with n sectors. All flows are in physical units.

PIOT were developed for Denmark, Germany and Italy since the late 90s (Pedersen, 1998, 2005; Statistisches Bundesamt, 2001; Nebbia, 2000). However, it was not until recently that several authors tried to use PIOTs to calculate (model) the total resource requirements and emissions associated to a given final demand (Hubacek and Giljum, 2003; Giljum and Hubacek, 2004; Suh, 2004b; Giljum et al., 2004; Dietzenbacher, 2005; Dietzenbacher et al., 2009; Xu and Zhang, 2009). However, the different methods used gathered different results. In particular, Xu and Zhang (2009) suggest a new, different way of calculating the primary inputs associated to a given final demand, which paradoxically results in a different inter-sectoral physical structure. Thus, the operation and analysis of PIOTs is still unclear; first, because it has not been pointed why the different methods gather different results, and second, because it has not been explored why different methods gathering the same results reveal different physical structures of the economic system (i.e. different inter-sectoral linkages). Consequently, at this point, it is not clear what method should be used to analyse the physical structure of the economic system. A deeper review on the construction and operation of PIOTs will be presented in section 3.2.1.

Input-output analysis is also used in Ecology, specifically in ecological network analysis, and has been used to explore the physical structure of dissipative systems such as trophic food webs. Hannon (1973a) used the input-output framework to represent the exchange of energy flows of a trophic food web, i.e. a network formed by the different species of an ecosystem. The input-output table was in energy units and he used an input-driven model to simulate different states. Only recently, efforts have been made to port the ecological IOA methods to analyse the economic system (Suh, 2005) and the industrial metabolism (Bailey et al., 2008).

The input-output framework can be complemented with estimation techniques to account for other phenomena, such as technological evolution, or can be used as the basis for more complex models, i.e where the system behaviour is not only related to the system flows but where substitution between flows is allowed (e.g. the E3MG (Barker and Scrieciu, 2010)).

2.4.2.2 Life Cycle Analysis

Earth System Science has developed methods to trace global, regional or local material flows related to BGCCs (Ehhalt, 1974; Mills et al., 2003) but do not provide the tools to measure specifically human-induced material flows. Different methods from environmental sciences have been used to fill this gap.

The *critical load* (or *critical threshold*) concepts are used when studying a specific environmental impact on a specific ecosystem or region (c.f. section 2.3.2). It allows the researcher to determine whether human-induced material flows significantly or critically degrade the ecosystem under assessment.

Instead of focussing on ecosystems, Life Cycle Analysis (LCA) methods are "product-based", since they trace the material flows and associated environmental impacts of a given process or product. .

LCA is fundamentally an accounting and modelling methodology relating the processes directly and indirectly required or induced by the object of study to the environmental impact(s) it induces in a selected system boundary (Guinée, 2002). The idea is to capture the environmental impacts generated during the whole life cycle of the product or process under study, i.e. the impacts associated to: the extraction the natural resources required to produce the product, the transformation and transportation stages, the use phase, and the disposal of the product. Therefore, it is said that LCA makes it possible to perform a cradle-to-grave analysis. Such a holistic approach is key for two reasons: first, it links explicitly production to consumption, making it possible to study the impact of final consumption on the generation of emissions from the production stage and, second, it avoids "problem shifting", i.e. to shift inadvertently an environmental impact by altering a production process without considering all upstream/downstream impacts (which is likely to happen unless a holistic approach such as LCA is used).

The LCA methodology consists on three steps: first, define the goal and scope of the analysis, second, developing the life-cycle inventory and, third, perform an impact assessment of the inventory previously compiled (Guinée, 2002).

Defining the goal and scope sets the broad guidelines for each study. The goal of the study implies setting the research question, the target audience and the intended application or use of the results. The scope of the study sets the temporal, geographical and technological coverage. Finally, the object of the analysis — one or more products and/or processes — are described as a function, functional unit and reference flows. This implies that LCA is very flexible since each LCA study has its own goal and scope; however, this implies that comparing different LCA studies might be complicated or even impossible since they have different underlying scopes and, thus, different system boundaries.

The life-cycle inventory phase is when the actual product system is defined together with some of the underlying assumptions. The cut-off boundaries are defined around the product of study, i.e. defining which are the components that will be directly considered in the analysis. The system can be drawn as a flow diagram with unit processes, whose data is to be collected. The relationship between unit processes is considered to be linear as a simplifying assumption (Guinée, 2002). A key step is defining the allocation methodology for processes producing more than one output, i.e. defining the input-output coefficients for each of the outputs. The allocation methodology is also flexible and depends on the goal and scope of the study. For example, in a given process producing several outputs, the allocation of inputs to outputs can be done according to mass, price or energy content. Each of these different rules will gather different results (Schaltegger et al., 1996). Again, this makes LCA a very flexible tool but makes it difficult to compare different studies if they do not share the same allocation rules. The result of this phase is a life-cycle inventory model, which can be summarised as a table listing the inputs and outputs of the product system.

The system definition usually entails all processes directly related to the product under study, and the indirect effects are included by both extending the analysis to upstream or downstream processes related to the directly related processes and/or by using background inventory data to quantify the indirect environmental effects of indirect flows. For example, the LCA of a tool composed of wood and metal might include the forestry and tooling sectors as the production stage of the product system. The indirect effects can be included either by expanding the system boundary, e.g. by including the mining industry providing the ore to the tooling sector, or using background inventory data on the environmental impacts associated to the extraction and refining of the ore.

The Impact Assessment phase is when the Life-Cycle Inventory is further processed and related to a set of environmental impacts, which in turn can be further re-aggregated as a series of midpoints and endpoints indicators. The environmental impacts categories are well established (e.g. acidification, eutrophication, climate change,...); however, the selection of categories and models quantifying the impact of each output to each category can differ. The subsequent allocation and aggregation method into different midpoint and endpoint might also differ between studies, although efforts have been made to standardise this procedure (Goedkoop et al., 2008).

So, LCA studies can be considered as a bottom-up or microscopic approach whereby the material flows associated to each of the processes required to produce, use and dispose of a product are added up. Since this is a very exhaustive exercise, the system definition does never include all processes of the economic system at once, but focusses on the processes directly related to the product under study and background inventory data is used to estimate the indirect effects at economy-wide level. Therefore, LCA is specifically indicated to perform comparative analyses whereby different production or consumption options are compared, given the same system boundary and assumptions, rather than calculating the absolute environmental impacts associated to the production and consumption of a given product.

In order to model the environmental impact of economic activity using LCA, all upstream and downstream processes associated to the product under study would need to be included in the system definition. Ritthoff et al. (2002) developed the Material Input Per unit of Service (MIPS) indicator which uses recursive LCA to assess the depletion of the resources required to produce a given product or service (i.e. only assesses a single environmental impact). MIPS is also called "ecological rucksack" (Aoe and Michiyasu, 2005). Since this method relies on the LCA assessment of the upstream and downstream flows, it is extremely time consuming to calculate (Ritthoff et al., 2002, pg. 16) and not very practical since a new analysis needs to be performed for every product.

The main application of LCA is to provide comparative analyses to identify the most environmentally friendly options to produce and/or use a product. For example, to quantify GHG emission reduction associated to using biomass co-firing instead of only coal in power generation (Mann et al., 2001), or to quantify the environmental impacts associated to the production and use of electric vehicles compared to conventional options (Hawkins et al., 2013). However, since LCA covers the use and disposal phase, it can also be used to understand the environmental impacts associated to different consumption patterns (Hertwich, 2005).

LCA is not only used to identify the most environmentally option but it is being integrated into the design of products or production processes precisely to build a "more sustainable" production system through life-cycle engineering (Hauschild et al., 2005). The Industrial Ecology field has developed several concepts to integrate more environmentally friendly practices into the design of new products by using LCA (Júnior and Demajorovic, 2013). Some of these concepts are cleaner production (Berkel et al., 1997), design for the environment (Hauschild et al., 1997) and design for recycling (Hagelüken and Corti, 2010); such concepts are reviewed more in depth in section 2.5.1.1.

According to Zhang et al. (2014), the main shortcoming of LCA is that "despite many efforts to improve data quality, inventories are still incomplete, inconsistent, unreliable, and even violate physical conservation laws because of boundary selection, cut-off criteria, missing data, allocation rules, methods for data combination, and other constraints (Lloyd and Ries, 2007; Finnveden et al., 2009)". Precisely to overcome some of these issues, input-output models can be used to complement or build life cycle inventories (Lenzen, 2002; Suh et al., 2004). In fact, since LCA usually assumes linearity, the linkages between the system subcomponents (which are build during the inventory phase) constitute a set of linear equations which can be represented as an IOT and solved using the Leontief model (Hertwich, 2005). So, there is a direct linkage between the LCA and IOA methodologies. In this sense, the main difference is that LCA constitutes a bottom-up approach with variable system boundaries, where the inventory is built from unitary (microscopic) processes within the system and using background inventory data. Conversely, IOA represents a top-down approach whereby the data is compiled at national level and its "unitary" processes are whole economic sectors.

The main limitations attributed to LCA is that it is purely a quantitative approach focussing on the environmental impacts associated to the underlying material flows, so the economic and social aspect driving the material flows are not considered. To overcome this limitation, Life-Cycle Costing (LCC) is a tool similar to LCA but tracing the costs associated to the life-cycle of a product. It was originally developed to inform purchasing decisions, specially to determine the optimal investment given the operational costs of products (Woodward, 1997). Although this method still has many shortcomings regarding the modelling of decisions and integrating some costs into the analysis (Gluch and Baumann, 2004), it is already used to provide life-cycle cost estimates to compare different technological options together with their environmental impact estimates, e.g. for the case of bioethanol versus gasoline (Luo et al., 2009). LCA has also been extended to consider the social impacts caused by the activities related to the life cycle of the studied product (Dreyer et al., 2005); the method is known as Social LCA (SLCA) and is still in its first steps (Jørgensen et al., 2007).

2.4.2.3 Economy-Wide Material Flow Accounting

Economy-Wide Material Flow Accounting (EW-MFA or EW-MFAcc) is not to be confused with Material Flow Analysis (MFA). Material Flow Analysis (MFA) is a method to trace material flows and stocks in a given system ensuring mass balance and data consistency (Brunner and Rechberger, 2004). MFA is used in process engineering and Industrial Ecology to trace the material going through a system (Hinterberger et al., 2003; Reck, 2012). EW-MFA is a methodology that uses the same principles as MFA but which aims to estimate the total amount of material flows directly and indirectly mobilised and transformed by a given economy (Eurostat and European Commission, 2001).

EW-MFAcc has been developed and integrated into the System of Environmental and Economic Accounts building on previous experiences of MFA of selected substances. For example, extensive work on several substances transformed and mobilised by economies was performed during the 90s (Baccini and Brunner, 1991). Such studies raised the awareness of the need to quantify and manage the transformation and mobilisation human-induced material flows to mitigate their environmental impacts. The World Resource Institute (WRI) funded the compilation of material flows for several countries (Adriaanse et al., 1997; Matthews et al., 2000). At the same time, the European Commission also organised the development of a methodology to harmonise and apply MFA at national scale (Bringezu et al., 1997). Finally, the Eurostat and European Commission (2001) released the EW-MFA methodology, which was later refined and applied in OECD countries (OECD, 2008d,a,b,c). As a result of this research effort, EW-MFA has been integrated into the System of Environmental and Economic Accounts (SEEA) (UN et al., 2003).

EW-MFA is based on the same grounds as MFA: the principle of mass conservation (Eurostat and European Commission, 2001), i.e. what comes in, comes out (even if in a different form). The mass conservation principle stems from the the first law of thermodynamics on the conservation of matter and energy; the law states that mass or energy is neither created nor destroyed by any physical transformation. Since mass is conserved when accounting material flows, it is also known as the mass balance principle. In this sense, it ensures data consistency since the sum of inputs equals the sum of outputs; the principle of mass conservation (or balance) can be written as:

$$\text{total inputs} = \text{total outputs} + \text{net accumulation} \tag{2.29}$$

EW-MFA has a double boundary: a domestic one with the environment and an international one. The domestic boundary is used to account for the materials that are extracted from and emitted back to the domestic environment (e.g. national ores, biomass,...). The international boundary serves to account for imported and exported material flows.

The material flows can be sub-divided in three categories, each revealing a different aspect of the flow:

- Domestic and Rest of the World (RoW). This category refers to the origin or destination of the flows, i.e. whether the flows are domestic, imports or exports.
- Used and Unused. Used flows refer to the flows that have some economic value and enter the economic activity, either for further processing (e.g. metal ores) or direct consumption (e.g. crops). Unused flows refer to the flows that are not involved in the economic activity but that have been transformed or mobilised to produce flows that enter the economic system. For example, mining activities induce used flows (e.g. metal ores) and unused flows (e.g. overburden); forestry activities induce used flows (e.g. timber) and unused flows (e.g. wood harvesting losses).
- Direct / Indirect. Direct flows represent the actual flows that are traced (i.e. the actual weight of the product). Indirect flows represent all material flows that have been indirectly used to produce the final products, i.e. considering all used (and unused) materials that have been transformed or mobilised upstream.

The terminology for material input categories is built from the three sub-divisions presented above, and is presented in table 2.8.

Domestic / ROW	Used / Unused	Product-Chain	Terminology
Domestic	Used	Direct	Domestic extraction (used)
Domestic	Unused	Does not apply	Unused domestic extraction
Row	Used	Direct	Imports
Row	Used	Indirect (upstream)	Indirect flows associated to imports
Row	Unused	Indirect (upstream)	Indirect flows associated to imports

TABLE 2.8: EW-MFA terminology for material input categories (Eurostat and European Commission, 2001, table 2)

In addition to these categories, the materials of the economy can be aggregated in several material types. Eurostat and European Commission (2001) recommends classifying the material flows associated to natural resources between minerals, energy resources, water, soil and biological materials. However, EW-MFAcc can be compiled at different levels of aggregation (UN et al., 2003).

So, according to the terminology presented in table 2.8, the material inflows and outflows of a given economy can be schematised as in figure 2.1.

Then, the following indicators can be developed:

- Direct Material Input (DMI) comprises the materials from domestic extraction plus imports.
- Total Material Input (TMI) is the DMI plus unused domestic extraction.
- Total material requirement (TMR) is the TMI plus the indirect (used and unused) flows associated to imports.
- Domestic processed output (DPO) corresponds to the material flows released by the economy to the environment.
- Total material output (TMO) is the DPO plus the unused domestic extraction
- Domestic material consumption (DMC) corresponds to the materials domestically consumed. Hence, it is equal to DMI minus exports.
- Total material consumption (TMC) is TMR minus exports and their associated indirect flows.
- Physical Trade Balance (PTB) is equivalent to the (economic) trade balance but in physical units: it reveals how much an economy relies on domestic material extraction compared to imports.
- Net Addition to Stock (NAS) represents the accumulation of materials within the economy. These are embedded in man-made capital, also known as stock-in-use (e.g. infrastructure, buildings, vehicles).

Additionally, using information on the indirect flows, EW-MFA makes it possible to devise other indicators such as the "hidden flows" or "material rucksack". The hidden flows reveal the hidden (indirect) material implications of trade (Bringezu et al., 2004): while only (the weight of) goods are accounted in trade exchanges, EW-MFA enables to estimate the upstream material flows induced by the traded goods. This is key to capture the material flows mobilised and transformed upstream, which are not necessarily captured within the domestic system boundaries. The "material rucksack" indicator uses the data from EW-MFA to calculate an indicator of the materials directly and indirectly required per capita; SERI (2009) found heavy disparities amongst the material rucksacks per capita of different countries.

The EW-MFA derived indicators have been used to inform the dematerialisation debate. Moll et al. (2005) observed that from 1980 to 2000, in the EU-15, a relative dematerialisation could be observed (i.e. using relative monetary indicators) but no absolute

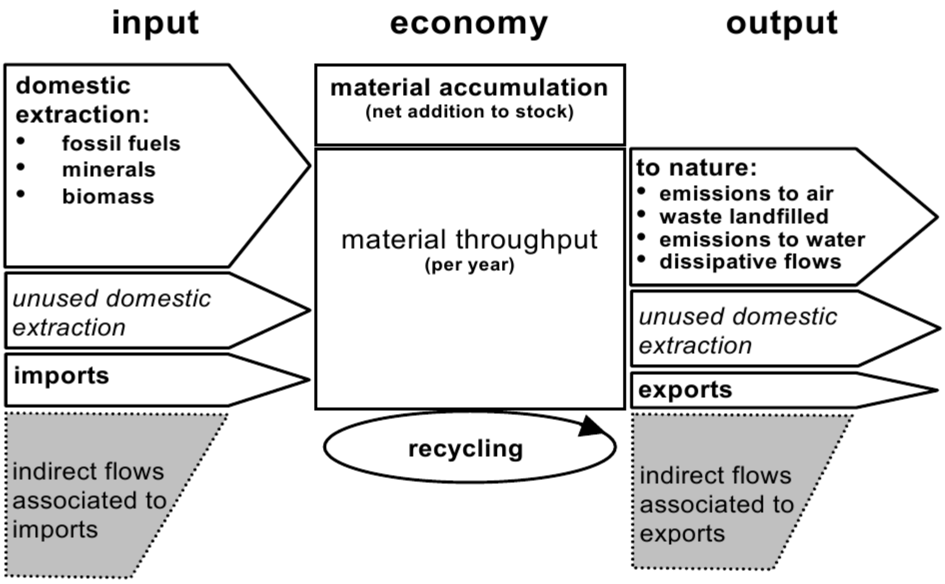

FIGURE 2.1: Economy-wide material balance scheme (Eurostat and European Commission, 2001, fig. 5)

dematerialisation was observed, i.e. using only absolute indicators; similar trends were observed internationally (Bringezu et al., 2004). In other words, there are no signs that the increasing trend revealed in figure 1.1 would be reversed, not even in industrialised countries (which are supposed to be more resource efficient that industrialising countries). The EW-MFA can also be used to explore the socio-economic patterns of materials use (Steinberger et al., 2010) and productivity (Steinberger and Krausmann, 2011).

EW-MFA relies on the LCA and IOA methods to build its material flows estimates (Hinterberger et al., 2003). LCA methods are used to estimate the (upstream) used and unused indirect flows associated to products or product groups to calculate the "ecological or material rucksack". However, using LCA to calculate indirect flows is appropriated only for biotic and abiotic raw materials and products with low level of processing, otherwise the issues with the boundary definition and amount of required data might arise (Joshi, 2000). To overcome this issues, IOA has been used to determine the total (direct and indirect) material requirements (and selected environmental impacts) associated to a given final product (Joshi, 2000; Hinterberger et al., 2003; Hertwich, 2005).

The main shortcoming of EW-MFA is its high level of structural and material aggregation, which masks the relationship between the material flows, environmental impacts and their corresponding responsible actors (Hinterberger et al., 2003). EW-MFA is a framework only considering the weight of the material flows, usually aggregating several types of substances (Eurostat and European Commission, 2001). Therefore, with this information alone, it is impossible to attribute environmental impacts to these material flows. This is especially true since the weight is not the only factor determining the environmental impact of substances but rather the combination of the amount and the specific chemical properties of the material flows (van der Voet et al., 2004a). EW-MFA usually presents the material flows aggregated at national level (Eurostat and European Commission, 2001). Therefore, with this information alone, it is impossible to allocate the material flows to each of the sectors composing the economy and, more importantly, it does not represent the physical structure of the economic system. Consequently, the EW-MFA framework cannot be used to link the material transformation and mobilisation within the economy to the different economic actors.

The EW-MFA has very recently been superseded by the Physical Input-Output Analysis framework within the System of Economic and Environmental Accounts (UN et al., 2014b). This is probably due to the fact that EW-MFA relies on IOA methods to be compiled but it has none of the advantages that the IO framework has, i.e. be able to to relate the material flows to their environmental impacts and responsible actors. In other words, EW-MFA indicators can easily be calculated from Physical Input-Output Tables (PIOTs) but PIOTs have inherent characteristics that cannot be estimated from EW-MFA alone. This is simply due to the fact that EW-MFA is a much more aggregated framework compared to PIOTs, both in terms of aggregate material flows (EW-MFA represents a few categories of aggregated materials while PIOTs can be developed for a single substance (Pedersen, 1998)) and of system subcomponents (EW-MFA usually aggregate the material transformed and mobilised by the whole economy while PIOTs represent the material flow exchanges of these flows between the economic sectors).

2.4.3 Coupling economic and Earth System models

Meadows et al. (1972) used system dynamics to model aggregately human activity (with population as underlying driver of industrial activity) and its interaction with the Earth System. The model entails the following sub-systems interacting with each other: population, food production, industrial production, pollution, and consumption of non-renewable natural resources. They projected that human activity led to increased extraction and emission of material flows from and to the environment, surpassing the carrying capacity of the Earth System, leading to collapse of both human and Earth Systems midway through the 21st century. Turner (2008) compares their findings with the collated historical data for 1970–2000 and finds that their results “compare favourably with key features of a business-as-usual scenario called the ’standard run’ scenario”.

Current global modelling practitioners use Integrated Assessment Models (IAMs) where models from different fields or using different methods are combined to explore in detail the driving forces of human activity and interaction with the environment. For example, the IPCC (2007b) used four IAMs to assess the impact of human activity on the Earth System climate: the AIM model (Jiang et al., 2000), the ASF model (Sankovski et al., 2000), the IMAGE 2.1 model (De Vries et al., 2000) and the MESSAGE model (Riahi and Roehrl, 2000). The four models have different structures (i.e. sub-modules, regional partitions or assumptions) and use different methods to estimate selected human-induced material flows (mostly GHG emissions) and their impacts on the Earth System. In some cases, they use bottom-up models where a certain disaggregation of specific parts of the economy (e.g. the power sector or sectors consuming energy) increase the resolution of the GHG emission composition. However, while IAM models manage to calculate some material flows associated to human activity, the calculations are not based on the modelling of the complete physical structure of the economic system, but either on small parts of it (with bottom-up models) or on indirect calculations using top-down models (e.g. by using environmentally extended monetary input-output tables). In other words, current IAM do not systematically model how the material flows are exchanged and transformed between the different economic sectors, although they provide some detail on specific transformations (e.g. fuel use and emissions).

2.4.4 Choice of modelling framework

In section 2.2, human-induced environmental degradation was fundamentally characterised as human-induced disturbances of the BGCCs caused by human-induced material flows (i.e. resource extraction or emission generation). Thus, the analysis needs to be performed at material flow level. In section 2.3, it was argued that the technological structure determines the physical structure of the economic system, which in turn determines the amount and type of human-induced material flows, in turn determining human-induced environmental degradation. Thus, the analytical framework needs to be able to model human-induced material flows and analyse its physical structure.

Precisely, Schipper et al. (2000) argued that measuring human activity using aggregated indicators was self-defeating if intending to understand how to modify the activity. They argued that precise, disaggregated structural indicators were required to understand the internal structure of a given system and, only then, (structural or systemic) solutions to reduce the undesirable impacts could be devised. In their studies, they compiled and related different data in the form of structural indicators (e.g. cars per capita) and used them to understand the structure of economies regarding the use of energy and to relate the structure to the induced carbon emissions (Schipper et al., 2001). This approach implies that the accounting frameworks reviewed in section 2.4.2 could be used in combination with other data to form such structural indicators, provided that the indicator was initially given at a sufficiently disaggregated level (e.g. the amount and type materials required by each sector of the economy, as given by EW-MFA indicators). However, even if sufficiently disaggregated, structural indicators do not reveal the actual physical structure of the economic system nor can they be used as a proxy for it, since the intersectoral linkages are not captured in such indicators (the sectoral EW-MFA do not reveal from which sector the material came from nor to which sector they are directed). Since the idea of the techno-structure is that the production and consumption stages are related, a systemic assessment is required to find how to modify the production-consumption structure to mitigate its environmental impacts. Thus, not only disaggregated indicators are required but a modelling framework able to represent and assess the physical structure of the economic system.

Hence, EW-MFA is discarded as a possible analytical framework because it only provides aggregated information on the material flows transformed and mobilised by the economic system. As seen in section 2.4.2.3, the high level of material and structural aggregation constitutes the main shortcoming of EW-MFA because it impedes to relate environmental degradation to the actual material flow causing it and, also, because it masks which actors are driving the material flows. Even in the case where the material flows were disaggregated by sector, the relationship between the sectors would not be captured, preventing structural analyses. In short, even if EW-MFA is a framework integrated into the SEEA and dedicated to trace material flows of the economy but it does not represent the physical structure of the economy and, hence, it is not further considered.

LCA provides a certain degree of disaggregation but does not systematically cover the physical flows going through the entire economy. As seen in section 2.4.2.2, LCA boundaries are arbitrary and product-based, i.e. they vary according to the product under analysis, and do not cover the whole economic system since this would require a tremendous amount of time. In other words, LCA is suited for microscopic analysis, i.e. studying particular differential aspects between different products or processes, but it is not well suited for macroscopic modelling exercises. This idea is supported by the fact that LCA is not integrated into the SEEA although it is used to estimate some indirect material flows within EW-MFA. So, LCA does not provide a comprehensive picture of the physical structure of the economic system: it only represents explicitly the physical structure of the flows within the product system and relies on background life-cycle inventories to account for the material flows induced within the economic system (but outside the product system). In short, even if LCA is a modelling framework which represents partially the physical structure of the economy, it is not further considered because it cannot be used to model the whole structure of the economic system consistently.

IOA is a framework enabling researchers to model and analyse the full structure of the economic system (LCA and EW-MFA do not provide this possibility) and, moreover, IOA is fully integrated with the Systems of National Accounts and of Economic and Environmental Accounts. But which is the appropriate type of IOA to analyse the physical structure of the economic system?

MIOTs represent the production of goods only, without considering the materials lost during the production process, i.e. the emissions. Thus, their sectoral structure does not reveal the real physical throughput of the sector since emissions might outweigh the production of goods. Consequently, the structure of MIOTs (i.e. the relative importance of sectors, given by their monetary throughputs) differs from the real physical structure of the economic system. For this reason, MIOTs are not further considered.

Pollution abatement models were developed to endogenise the treatment of selected pollutant emissions. The IOTs describing pollution abatement options are IOT with hybrid units — partly monetary and partly physical. The description of the physical flows is concerned exclusively with the emissions but the rest of physical flows are not included. In fact, most of the economic activity is described in monetary terms, which has the same caveat as MIOTs. Therefore, this type of approach is not appropriate to model the physical structure of the economic system.

While EE-MIOTs might provide accurate estimates of the amount of material flows mobilised and transformed by the economy, EE-MIOTs have the same caveat as MIOTs since their core structure is the same underlying MIOT. Therefore, EE-MIOTs can neither be used to explore the physical structure of the economic system because they are based on the monetary structure.

Hybrid-MIOTs have two caveats regarding the representation of the physical structure. First, the underlying model for the physical flows establishes relationships following the principle of embodied energy conservation and no (material) emissions are accounted for explicitly (the emissions are derived after the total amount of used energy is found). This implies that the flows that are traced represent the flows embedded in final production only, not the emissions. In other words, it is not possible to identify which sectors generate emissions, it is only possible to identify the total resources consumed by the economic system and then estimate the emissions generated. Second, the model for the monetary flows has the same caveats as in conventional MIOTs: the level of sectoral activity might over- or underestimate the physical flows going through each sector and, thus, the monetary structure of the hybrid table might be different from the actual physical structure. So, the hybrid model is not appropriate to model the dissipative nature of the physical structure of the economic system and the monetary part of the hybrid table has the caveat as a MIOT. Thus, hybrid-IOTs are not further considered.

PIOTs with disposals to nature are the only framework that represents the physical structure of the economy as is, i.e. including the sectoral emissions (which were not represented in MIOTs nor hybrid-IOTs). Additionally, PIOTs is an accounting framework at national level, covering all material flows induced by the economy. Moreover, the physical supply and use table framework (which enables to build PIOTs) has been suggested as the backbone framework to compile all environmental accounts (UN et al., 2014b). Since the PIOT framework is the only framework able to represent (and potentially model) the physical structure of the economic system, it is chosen as the analytical framework for this thesis.

The different characteristics of LCA, EW-MFA and the different IOA frameworks are summarised in table 2.9.

	MIOT	EE-MIOT	Hybrid-IOT	PIOT	LCA	EW-MFAcc
Flow units	Monetary	Monetary in MIOT and physical in extended variables	Monetary & Physical	Physical	Physical	Physical
Accounting principle	Double entry bookkeeping	Double entry bookkeeping	Double entry bookkeeping & embodied energy conservation	Mass balance	Mass balance & selected allocation rules	Mass balance
Accounting framework	Symmetrical IOT	Symmetrical IOT	Symmetrical IOT	Symmetrical IOT	Life-cycle inventory	National aggregates
Relationship between flows	Linear	Linear	Linear	Linear	Linear	None
System boundary	National	National	National	National	Product-dependent	National
Explicit representation of the physical structure	No	No	Partial	Yes	Only within the product system	No
Integration with National Accounts	Fully with SNA	Fully with SNA and current SEEA	Fully with SNA and partially with current SEEA	Suggested as new backbone framework for SEEA	None	Fully with current SEEA but superseded by PIOTs in new SEEA

Table 2.9: Comparison of selected accounting and modelling frameworks representing the physical structure of the economy (previously reviewed in section 2.4.2).

2.4.5 Gaps in the analysis of the physical structure of the economic system using Input-Output Analysis

Since IOA has been chosen as the analytical framework for this research, this section examines the previous advancements in exploring the physical structure of the economic system within IOA so as to identify current gaps in the analysis of the physical structure of the economic system represented by a Physical Input-Output Table.

2.4.5.1 Structural analysis of PIOTs

To start with, using traditional input-output models on PIOTs to determine the amount of primary resources or emissions associated to a given amount of final demand is controversial, as proved by the different results found by different methods (Hubacek and Giljum, 2003; Giljum and Hubacek, 2004; Suh, 2004b; Giljum et al., 2004; Dietzenbacher, 2005; Weisz and Duchin, 2006; Dietzenbacher et al., 2009; Xu and Zhang, 2009). Until now, it has not been clearly explained why the different methods gather different results.

Additionally, methods gathering the same level of resource use and emission generation for a given final demand reveal different (inter-sectoral) physical structures of the economic system. This difference between the structures has not yet been assessed and constitutes a theoretical gap in the analysis of PIOTs[12].

Since the aim of this thesis is to analyse the structure of the economic system to identify systemic ways to mitigate environmental degradation using the IO framework, the first step will be to clarify the discordance between the different methods used to operate and analyse PIOTs in the first part of chapter 3. In particular, the different methods will be assessed in depth at theoretical level: it will be demonstrated why some methods lead to inaccurate results, what are the underlying mechanisms and assumptions of the valid methods, what is the interpretation of the different structures associated to each method and the methods that are valid will be generalised for the case of multiple simultaneous emissions.

However, although IOTs entail typically less than a hundred sectors (Tukker and Jansen, 2006), some might provide several hundreds (Huppes et al., 2006). In any case, the

[12] At first sight, this structural difference contravenes Weisz and Duchin (2006), since they demonstrate that PIOTs and MIOTs should theoretically share the same structure, only that MIOTs would have it altered by the vector of prices associated to the quantities exchanged. However, as it will be explained in chapter 3, the statement from Weisz and Duchin (2006) only applies to PIOTs without disposals to nature (i.e. without emissions or waste generation outside the economic system). However, the PIOTs studied in this research do contain disposals to nature. The reasons why this research uses PIOTs with disposals to nature is explained in detail in chapter 3; in short, the reason is because PIOTs without disposals to nature exclude part of the flows actually extracted, processed and released by the economic system, constituting a partial representation of the actual impact of economic activity.

analysis of disaggregated indicators or structure might become a tedious exercise, where the amount of data might complicate the analysis or even mask structural patterns. In this context, alternative methods such as visual analysis might help in overcoming this issue, specially since visual inspection might reveal structural patterns and help identifying key structural features. In this sense, traditional structural analysis methods in IOA, such as the backward and forward linkage analysis, provide only aggregated indicators of the structural relationship between the different sectors: the backward and forward linkage measures aggregate all intersectoral linkages, but do not provide any measure on which of these linkages are more important or whether there is a pattern in the structure of these inter-sectoral linkages[13]. So, a disaggregated visual analysis tool could complement or provide further insights into the structural analysis of IOTs. The second part of chapter 3 aims to develop a visual representation enabling researchers to perform disaggregated visual analyses and explore the use of such tool. The next section provides a literature review on previous visualisation tools.

2.4.5.2 Traditional visual representations of the economic system structure

Traditional visual representation of systems is done with flowcharts, where each sub-component is represented by a box and the relationships amongst sub-components by arrows connecting the different boxes. This approach is widely used in material and substance flow analysis studies (Graedel et al., 2002; Brunner and Rechberger, 2004; Daigo et al., 2010).

However, the arrows are to be scaled to the relative weight of the flows to deliver the information visually, otherwise exhaustive reading of all numerical values would be required. The first diagrams where arrows are proportional to their value were devised by Sankey (Sankey, 1898), who depicted the energy flows to scale of an idealised and actual steam plants. From then on, Sankey diagrams have been widely used for energy and material flow management (Schmidt, 2008a). So far, Sankey diagrams have been typically used to identify resource inefficiencies and potential for resource savings (Schmidt, 2008a). For example, they have been used to trace global energy flows (Cullen and Allwood, 2010) but usually they focus on narrower scopes, such as the flows of a given process or within an economy (Graedel et al., 2002). They usually represent material or energy flows but can also include stocks (Schmidt, 2008b).

In Sankey diagrams, the boxes representing the system sub-components are usually omitted for clarity but can be present. Typically, Sankey diagrams avoid crossing the arrows, otherwise they become confusing. In some cases, this leads to awkward flow

[13] Note that the same structural measure (e.g. a sectoral backward linkage measure) might hide different intersectoral structures and different structural measures might hide the same intersectoral structure.

structures (Schmidt, 2008a, fig. 2), i.e. flows with random directions or flows framed by other flows. This is why Sankey diagrams are usually oriented in a single direction (Schmidt, 2008a, fig. 3, 4, 5). Although Sankey diagrams have no restriction in the number of system sub-components they represent, most of the Sankey diagrams reviewed have no more than five sub-components (Schmidt, 2008a; Asari et al., 2008; Cullen and Allwood, 2010). However, Sankey diagrams might become confusing when representing material flows of complex systems, since they usually entail cyclic loops, and cyclic loops involving several sectors usually cross other flows, making it difficult to identify the source of the flows and compare them to each other. Material flow diagrams with arrows proportional to the size of the flow can be drawn with Material Flow Analysis software, such as STAN (Cencic and Rechberger, 2008).

Input-output analysis has also developed its visual analysis tools. They usually consist on 2D colour coded matrices, where colours represent the cell value, enabling the researcher to visually identify patterns (Kondo et al., 2011). Also 3D matrices using peaks instead of colours are used to represent cell values (Sonis et al., 2000). In the 3D case, issues arise since high peaks hide lower peaks positioned behind them. Although reordering the matrix to avoid such issue is possible, it requires further treatment and alters the position of the sectors, making it harder to perceive the structural features of each sector and its linkage pattern with the other sectors.

However, both Sankey diagrams and colour-pattern matrices are still not convenient for a visual structural analysis because in both cases it is hard to assess visually the input and output structure of the flows reaching each sub-system component. In Sankey diagrams the difficulty is mainly due to the lack of standardisation of the orientation and type of flows. E.g., visual cues indicating whether the flows are inter-sectoral or cross the system boundaries are not necessarily present or, when present, the system boundary is defined by a dashed box, so the researcher needs to follow each flow to determine whether it is a inter-sectoral flow or not, hindering the structural assessment. In 2D colour-pattern matrices, it is even harder to determine the input or output structure of each sector because the "weight" of the flows are given by colours, which is not a precise manner to determine a quantity since human colour perception cannot determine absolute colour values (i.e. human sight does not perceive small colour variations when colours are not side to side). So, while the colour pattern might help to identify broad system characteristics, they make difficult the assessment of the relative weight of the sectoral input and output structure since colours are not an accurate visual cue for the "weight" of each flow. Ideally, a diagram enabling visual structural analysis would be configured so that the researcher is able to identify the input and output structure of each sector easily, i.e. where the relative and absolute values of the input and output flows of each sector and the type of flows are given by visual cues. In the second part of chapter 3, it is investigated how to devise an alternative diagram meeting this ideal configuration and how to use it for disaggregated structural analysis.

2.4.5.3 Identification of important coefficients and clusters within the IO structure

This section aims to review analyses developed within the IO framework to identify key structural features. Some of these are important since they support some ideas presented in section 4.5 (chapter 4) to develop a method to decompose the structure of the economic system to extract key structural components (e.g. the cyclic structure).

Dwyer and Waugh (1953) and Evans (1954) were among the first ones to develop methods to assess the systemic impact due to changes in the technical coefficients. These methods were initially developed to assess how an error in the technical coefficient would propagate through the system. In particular, the aim is to examine how a change in a given technical coefficient affects the coefficients of the Leontief inverse matrix or the total outputs of the sectors composing the system. Also, according to Miller and Blair (2009, chap. 12.3), this methods can also be used to assess the relative systemic importance of the different coefficients. In this case, the underlying idea would to identify "important coefficients" whose variation would have a greater impact on the rest of the system. Sonis and Hewings (1989, 1992) improved the original methods to calculate such impacts (based on Sherman and Morrison (1949, 1950) and Woodbury (1950)) by developing the concept of "field of influence" which enables researchers to perform the same calculation in a single operation (Miller and Blair, 2009, chap. 12.3.6).

However, while quantifying the induced systemic error due to the (localised) error of a single measure of a given technical coefficient seems a reasonable approach, using the same method to assess the systemic impact of a change of a given coefficient might be misleading. Taking as starting point the explanation of the mathematical background presented in Miller and Blair (2009, chap. 12.3.1): "Given a nonsingular matrix, $\mathbf{M}$, and its inverse, $\mathbf{M}^{-1}$, assume that one (or more) elements of $\mathbf{M}$ are changed, i.e., $m^*_{ij} = m_{ij} + \Delta m_{ij}$, producing $\mathbf{M}^*_{ij} = \mathbf{M}_{ij} + \Delta\mathbf{M}_{ij}$". The issue is that, in fact, as argued in section 2.3.4, the technological structure shapes the physical structure, i.e. both are tightly linked. In other words, the physical structure is due to how the different material flows are processed and used through the economic system. If a single link (or technical coefficient) of a material flow crossing the economic system is modified, both its upstream and downstream flow will be affected. For example, if a sector improves its technology and is now more resource efficient, it will require less inputs to produce the same output. Thus, the upstream flows constituting its direct and indirect supply chain (which most probably goes through several sectors due to the system interconnectedness) will be reduced accordingly, affecting several other technical coefficients. These upstream savings can be greater or lesser depending not only on the initial technical coefficient changed but on the induced variation on other technical coefficients. Thus, analysing the change of a single technical coefficient does not reflect the actual changes of the structure associated to the change of that coefficient. In other words, one can assess the impact of a change in a given inter-sectoral flow or in a technical coefficient on the system, but the change is not propagated through the system according to the underlying structure of the system, therefore the change in the flow or technical coefficient does not reflect the behaviour of the system following this change. Additionally, even if the total changes associated to the change of a single coefficient might seem high, it might be lower than other cases in which the whole induced change in the structure is taken into account. Thus, studying the modification of a single technical coefficient on its own might provide misleading results. In this sense, it might be better to try to identify structural features which describe how the materials flow through the whole economic system (e.g. the acyclic and cyclic flows) because the researcher would know which upstream and downstream flows would also be affected.

Simpson and Tsukui (1965, p. 434) were the first ones to explore the idea that "there are certain fundamental elements which may be found in the productive structure of modern economic systems which are purely technical in character", which they call the fundamental structure of IOTs. Simpson and Tsukui (1965) explored the technical coefficient matrix of the USA and Japan and, despite the initial differences in the original IOTs, they found similar patterns in the sectoral linkages. In particular, by removing small technical coefficients and ordering the matrices appropriately they found four block triangular matrices within the original technical coefficient matrices that entailed the same sectors. In other words, the production structure of both countries showed the same pattern, which reveals a "pyramidal" hierarchy among the same sectors. As Nakamura and Kondo (2009) put it: from a material flow perspective, some sectors always require materials with a higher degree of fabrication than others. In other words, this pyramidal hierarchy can be understood as a pre-determined supply-chain, whereby materials follow an ordered process of fabrication/transformation. E.g. natural resources are extracted, refined, transformed into basic goods (e.g. copper wires), further processed into more elaborated goods (e.g. electrical components), and finally assembled or transformed into the good at the top of the supply chain (e.g. a car). Thus, the fundamental structure of IOTs implies that materials go through the economic systems in a linear flow, increasing their degree of fabrication as they cascade through different sectors. Several methods have been developed afterwards to identify block-triangular matrices within the IO framework to assess its production structure (Korte and Oberhofer, 1971; Duff and Reid, 1978; Kondo, 2014).

The block triangular matrices identified within the input-output structure can also be understood as clusters, i.e. groups of tightly connected sectors. Analysing cluster composition and relationships complements traditional structural analyses such as the backward and forward linkage analyses (which provides information on the linkages at sectoral level), since cluster analysis enables researchers to explain the linkage relationships at a different level (of cluster). Several methods have been developed to identify clusters (Hoen, 2002). Traditionally, sectors are associated to a single cluster, however Díaz et al. (2006) developed a method identifying sectors participating in several clusters.

2.5 Mitigating environmental degradation and resource depletion

2.5.1 Approaches to manage human-induced material flows

2.5.1.1 In Industrial Ecology

Environmental sciences have developed strategies to manage human-induced material flows to mitigate their impact on the Earth System. In particular, Industrial Ecology explicitly aims to modify the structure of the economic system (Ayres, 1994a) for which it has developed the following concepts:

Closed material cycles Ayres (1996) introduced this concept by applying it to different materials (e.g. metals and organic substances) in different types of cycling: recycling of materials (e.g. aluminium) or recovery of waste as by-products used for other production processes (e.g. sulphur emissions from coal combustion used to produce construction materials). However, a cyclic structure is not necessarily completed (as in the sulphur case) and the material path description, although usually detailed by the use of LCA, is not systematically applied to different types of materials nor related to the different types of cycling. In fact, there are different ways to close the cycles: recycling a single time (as capturing and transforming sulphur emissions to be used as gypsum), recycling a few times degrading the properties of the recycled material (known as downcycling, e.g. paper recycling), or recycling by maintaining the material properties, as in the case of metals, sometimes called "functional recycling" (Graedel et al., 2011). However, there is no systematic description nor representation of these different material paths and transformations within an economy, each of which has different resource and environmental implications (Rochat et al., 2013).

Cleaner Production (CP) CP is strongly based on LCA and suggests methodologies to modify production processes to prevent pollution (Cheremisinoff and Rosenfeld, 2009, 2010, 2011), or to modify the product design — reviewed below — to mitigate different environmental impacts associated either to the production, use or disposal of the products. Apart from the different design approaches, CP is recently seeking a more comprehensive approach by developing Environmental Management Accounting tools, similar to LCA but where "the material flows must be assessed according to their compatibility with those materials which are common in the natural environment" (Schaltegger, 2008, pg. 15). Additionally, they note the key importance of developing "consistency strategies", i.e. overarching strategies able to orchestrate all material structure of the economy, such as the cradle-to-cradle approach suggested by McDonough and Braungart (2002) (reviewed below). However, they do not operationalise the cradle-to-cradle approach with EMA tools nor suggest any other comprehensive strategy.

Design for Environment (DfE) DfE applies LCA in process and product design to reduce potential environmental impacts (Gasafi et al., 2003). Since DfE focusses on the identification of potential environmental impacts (rather than the establishment of a specific "ideal" structure), the design process might be sub-optimal from an environmental systems perspective (Hauschild et al., 1997). Despite this caveat, DfE has been used to devise products and policies (Calcott and Walls, 2005).

Design for Recycling (DfR) DfR stems from the DfE principles but focuses on the recycling potential of products to reduce their resource and environmental impact (Masanet and Horvath, 2007; Gaustad et al., 2010; Hagelüken and Corti, 2010).

Design for Sustainability (D4S) D4S extends the scope of DfE by including social and economic variables (UNEP and TU-Delft, 2010). An extended social approach does not contribute to improving the physical structure of the material flows but reveals socially relevant implications associated to the material flows (Muradian and Martinez-Alier, 2001; Martinez-Alier, 2002, 2005; Martinez-Alier et al., 2010).

Dematerialisation Herman et al. (1990) formalised this phenomenon and, although related to different production and product variables, they defined it as "the change [reduction] in the amount of waste generated per unit of industrial products". So, absolute dematerialisation refers to the absolute reduction of material required (or waste produced according to the previous definition) to produce a given amount of goods. Relative dematerialisation refers to the variation of material requirements (or waste production) per monetary unit. Van der Voet et al. (2004b) challenged the concept due to the different environmental impact potential of different materials, i.e. a dematerialisation substituting low impact materials by high impact ones would lead to higher overall impact. De Bruyn (2002) observed that alternate phases of relative dematerialisation and rematerialisation occur.

Transmaterialisation Labys (2002) defines it as a "natural replacement cycle in industrial development" and unrelated to the structural change implied by absolute dematerialisation; it can be used to explain the material shifts (e.g. lower consumption of certain materials in favour of others, e.g. plastic substituting wood).

Industrial Ecology uses these concepts from a system approach, in particular by linking ecosystem activity to industrial activity (Hardy and Graedel, 2002; Lowe and Evans, 1995; Korhonen and Snäkin, 2005; Côté and Hall, 1995; Allenby et al., 1994) and to human-induced material flows (Husar, 1994), and even using ecological metrics to quantify the industrial metabolism (Wood and Lenzen, 2009; Bailey et al., 2004a,b; Korhonen and Snäkin, 2005).

Allwood and Cullen (2011) summarise the practical implementation of the previous concepts as

1. Using less materials by design
2. Reducing yield losses
3. Diverting manufacturing scrap
4. Re-using metal components
5. Producing products with longer life
6. Reducing final demand

All points are potentially affected by the product design, justifying the different design approaches reviewed above. The first four items affect production processes, the fifth and sixth items affect the consumption phase, where the last item emphasises consumer responsibility[14].

Although Industrial Ecology is starting to consider the industrial metabolism from an Earth System perspective (Ayres and Ayres, 2002, chap. 21, 46), it has not yet developed the methods to assess the interactions between the industrial metabolism and the BGCC.

To sum up, two different strategies for material flow management are implicitly entailed in the above concepts: 1) changing the type of materials used for ones inducing less

[14] While the quantification and allocation of final demand falls within the Industrial Ecology field, the social drivers and mechanism are out of its scope; other social sciences fields investigate how to reduce final demand, e.g. developing the "sufficiency" concept (Steinberger and Roberts, 2010; Alexander, 2013)

environmental impact or, 2) (re)using the current materials in a different manner, either by re-using wastes as by-products or by recycling waste as raw material, improving the resource efficiency of the system and reducing its environmental impacts. In both cases, the physical structure of the economic system is altered: in the former case because different materials are used, requiring different raw materials and generating different emissions and, in the latter, because different material paths are created, either by recycling or by finding a different use for a given material. In fact, as discussed previously in section 2.3.4, changes in the physical structure will stem from changes in the technological structure because the technological structure determines the physical structure. Similarly, in most cases, a change in the physical structure also implies a change in the economic structure, since a new physical structure of the economic system implies that the relative importance of the different economic sectors vary (e.g. if a new material is used, new sectors extracting and transforming this material will be developed in the economic structure; similarly, if some material use is reduced in favour of another material, the associated economic activities will vary accordingly). As previously stated, this thesis focusses exclusively on the physical structure of the economic system, which can be used to inform how to alter the technological structure because it enables researchers to assess the relative and absolute contribution of economic sectors and structural features (e.g. cycling) to the environmental footprint of the economic system.

2.5.1.2 In other fields

McDonough and Braungart (2002) devised the "cradle-to-cradle" (C2C) concept based on "eco-efficient" product and process design from a life-cycle perspective. To formalise this concept, McDonough and Braungart (2002, chap. 4) divide the physical metabolism of economies between the "biological metabolism" associated to the natural cycles and the "technical metabolism" associated to the industrial metabolism. They also divide the material flows accordingly: "a biological nutrient is a material or product designed to return to the biological cycle" and a "technical nutrient is a material or product designed to go back into the technical cycle". By using this material division, C2C seems to provide an overarching strategy to allocate material flows to fulfil the different functions of the economic system and, by doing so, environmental impact would be avoided. However, while the C2C has succeeded in uncovering the life-cycle impacts of products to a wider audience, three fundamental issues arise:

1. The division of material flows is inconsistent because some biological nutrients are also technical nutrients: although in different quantities, some substances are required to fulfil both functions, e.g. iron, sulphur, oxygen, carbon.

2. The division between "technical" and "biological" materials does not address the impacts associated to the extraction and emissions of the "biological materials". Even if the "biological material" is potentially integrable with the environment (e.g. biodegradable soap (McDonough and Braungart, 2002, pg. 105)), too much emissions of any biological material potentially disturb the BGCCs (e.g. eutrophication induced by the soap elements).
3. The C2C concept has not been defined in an operational manner from a LCA perspective (Bakker et al., 2010); thus, it cannot be used for accounting nor analytical purposes.
4. Tools were not developed to assess an economy-wide transition towards a "cradle-to-cradle" economy.

Other similar architectural and landscape concepts such as "regenerative design" (Lyle, 1994) are aligned with a life-cycle eco-design of products.

Changing the focus from production to consumption, some authors argue that reducing consumption rates is a complementary strategy to reduce the economic system environmental footprint (Alcott, 2008; Steinberger and Roberts, 2010; Jackson, 2009a,b; Ehrenfeld, 2013). In fact, as argued in section 2.3.3, consumption and, thus, consumption behaviour is also key in inducing the structural change since consumption patterns influence the physical structure of the economic system (e.g. the preference of recycled or recyclable materials over new materials or non-recyclable ones).

Biomimicry is a new field where biological processes or materials are mimicked for industrial purposes (Benyus, 1998). Biomimicry studies the chemical and physical composition and properties of natural substances or animals with the aim of either reproducing them synthetically or finding new, better performing materials (Swiegers, 2012). The biomimicry concept has also been ported to the construction sector (Zeldenrust, 2010). Biomimicry brings "natural" materials or processes — i.e. material already present in the main BGCCs — into industrial practices. So, the resulting productive system has more chances to have a lower environmental impact than using synthetic materials, which are usually synthesized using confined materials (e.g. fossil fuels or minerals) and, consequently, their release into the environment causes systematic unbalances of the BGCCs. In this sense, biomimicry is aligned with the Cleaner Production principle of Industrial Ecology; the difference is that biomimicry does not focus exclusively on reducing the environmental impacts, as Cleaner Production does, but rather seeks new applications of natural materials.

2.6 Cycling as a key structural feature for a more resource efficient (i.e. less environmentally disruptive) economic system

In section 2.5, it has been shown that different options exist to mitigate environmental degradation by modifying the structure of the economic system, either by changing the types of materials used or by using them differently. In particular, strong emphasis is given to closing material loops, either by (re)using previously discarded by-products or by recycling waste. More elaborated theories such as the cradle-to-cradle concept are also based on shifting the production-consumption structure towards a cyclic one. These concepts convey the idea that a circular structure is more environmentally friendly because a cyclic arrangement of the material flows within the economic system reduces the amount of resources it requires and the amount of emissions it generates, potentially mitigating environmental degradation in both cases, since it reduces the disturbances caused to the BGCCs. Life Cycle Analyses (LCAs) have confirmed empirically that recycling practices reduce the use of primary resources and the emission of pollutants: e.g., WRAP (2010) reviews 55 LCA studies on paper, plastic, biopolymer, food, wood and textile recycling and concludes "that recycling offers more environmental benefits and lower environmental impacts than the other waste management options". This body of knowledge is aligned with the approaches to manage material flows reviewed in section 2.5.1.

However, guiding and managing a structural change towards a circular economic structure requires to monitor the physical structure of the economic system as a whole because it is the physical structure (and associated technologies) that determines which materials are used, and how they are transformed and released to the environment (see section 2.3.4): e.g. whether used in a cyclic or acyclic manner. The structure needs to be assessed in a systemic manner, otherwise the indirect effects of cycling or structural change would not be captured. Thus, the modelling approach selected in section 2.4.5, IOA, is still appropriate because it is a systemic one, representing explicitly the flows of materials and energy throughout the economic system, enabling the researcher to examine directly the structure of the system[15].

[15] This is a key difference compared to Life Cycle Analysis, which aggregates the environmental impacts of a given product, sector or specific components of the system without revealing explicitly the structure of the physical flows within the system boundary (Guinée, 2002). Therefore, LCA has not been used in this research.

2.6.1 On the concepts of cycling and recycling

The concepts of cycling and recycling are ambiguous and might lead to misunderstandings. According to Oxford University Press (2015), the main definition of *to recycle* is to "convert (waste) into reusable material". It also entails two subdefinitions: to "return (material) to a previous stage in a cyclic process" and to "use again". The main definition can lead to misunderstandings if recycling is understood as a cyclic process, as the subdefinition suggests, because to convert waste into reusable material does not necessarily requires a cyclic process. For example, coal power plants produce gypsum as a waste of the desulphurisation process. The gypsum can be reused in the building products industry; it is thus recycled, although the material flow did not close any cycle. Another issue is that the first subdefinition implies that recycled materials might return to the same previous stage, but in fact many recycled materials, although following a cyclic path through the economy, do not necessarily return to the previous stage — they only go through the same sector. For example, recycling paper degrades the quality of the paper, therefore the material never returns to the previous stage or composition, although it is recycled through the economic system in a cyclic manner. So, this case falls somewhere between the main definition and the subdefinition.

According to Oxford University Press (2015), the main definition of a *cycle* is "a series of events that are regularly repeated in the same order". Out of seven subdefinitions, only one refers explicitly to the idea that a cycle is completed through successive events in a closed loop ("A series of successive metabolic reactions in which one of the products is regenerated and reused"). In this research, a cycle will always imply the idea of successive stages forming a closed loop.

The ambiguity in the definition of recycling is not only an issue in the common language, as illustrated above, but also in technical documents. For example, in the waste directive of the European Union (European Parliament, 2008):

> 'Recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

This definition has the same issues as noted above: not all recycling implies cyclic processes. Also, it is important to note that cyclic processes do not constitute recycling if the materials involved are not waste. Cyclic processes (or cyclic material flows) are common inside the productive system of an economy. For example, the forestry industry sells wood to the tool manufacturer, which sells wooden tools back to the forestry industry so that it can continue the extraction of wood, creating a cyclic material flow of wood between the two industries. Although, this cyclic interaction is not included in the concept of recycling, it can be included in the concept of cycling.

Therefore, the concept of cycling is broader than the concept of recycling because cycling refers to any material while recycling is restricted to cycles including waste materials. Due to the potential broader systemic effects of cycling, this research will focus on cycling (which includes recycling). This approach will be further justified below, when discussing the systemic effects of cycling.

Also, traditional recycling indicators or measures refer to processes including cycles, i.e. excluding recycling which does not lead to closed loop material flows (Bailey et al., 2008) (as the example provided in the first paragraph). This poses an analytical inconsistency: if traditional measures apply only to "cyclic recycling", how can the effects of "acyclic recycling" be studied? However, from a structural perspective this inconsistency is only a lexical issue. From a systemic perspective, acyclic recycling is a straight, acyclic flow and therefore has the same structural properties as acyclic flows. The fact that it is called a recycled flow is a qualitative issue which does not necessarily induce different systemic effects: in a dissipative system such as the economic system, each process transforms the material inflow partly in a final product and partly in an emission. An acyclic recycling flow is characterised, according to the definition of recycling, as a process in which the inflow is qualified as waste. However, this type of categorisation is not relevant from a structural perspective since from a structural perspective acyclic recycling flows will have the same properties as "plain" acyclic flows. Therefore, this research will not address the issue of identifying "acyclic recycling" falling within the broad definition of recycling.

The literature studying cycling within the economic (industrial) system has traditionally focussed on recycling. In particular, it has focussed on the recycled content, defined as the ratio between recycled inputs and total production inputs, and the recovery rate, defined as the ratio between material recovered after consumption and total material consumption (Bailey et al., 2008). Such metrics do not provide direct information on how the (re)cycling is affecting the system performance. However, it is traditionally assumed that more recycling implies better environmental performance, i.e. less emissions generated and/or less resources consumed, since a recycled product usually requires less natural resources to be produced.

As previously stated, the common understanding that recycling is a good strategy from an environmental perspective is backed by numerous life cycle analyses. A review of 55 LCA studies on paper, plastic, biopolymer, food, wood and textile recycling concludes "that recycling offers more environmental benefits and lower environmental impacts than the other waste management options" (WRAP, 2010)[16].

An incipient categorisation differentiating different types of recycling has been suggested. However, the categories are not based on the study of the systemic properties of the different types of recycling but rather on the a priori understanding of how cycling works. For example, some materials might be recycled endlessly[17] because their material properties are not altered by the recycling process. The typical case is metal recycling. Such type of recycling has been called "functional recycling" to capture the idea of endless recycling without loosing its initial quality and maintaining its function (Graedel et al., 2011). Also, as an opposite term, "non-functional recycling" represents metals that are recycled but "lost" in bigger material streams (usually as metal impurities in other metal stream), and therefore cannot be endlessly recycled as the initial material (Graedel et al., 2011). The idea of functional and non-functional flows was originally coined to designate more general material flows, not only recycling ones (Guinée et al., 1999).

Another term conveying the idea that some recycled flows loose some of its original properties is the term "downcycling". In general terms, downcycling can be defined as a recycling process degrading the original material properties. Regarding the previous categorisation between, non-functional recycling has been associated to downcycling (Graedel et al., 2011). However, downcycling can occur in some recycling processes of materials such as plastics, concrete, tires (Meyer, 2009). Paper is downcycled by the very recycling process (the fibres are shortened every time paper is processed), and glass can be also be functionally or non-functionally recycled (e.g., recycled as further glass bottles or as cement aggregate).

Also, "upcycling" processes exists, whereby a recycled material is upgraded, regaining its original properties. This can be done by refining the material prior to recycling (i.e. removing its impurities) or conditioning it so that it can achieve its initial properties. This is the case for metals with impurities (Koffler and Florin, 2013). Also, other methods to upgrade the material properties can be developed, as for secondary paper fibres (Monte et al., 2009).

However, it is important to note that these categories have been broadly defined, so a formal categorisation based on the systemic properties of (re)cycling is still missing. This might be due to the fact that recycling studies usually rely on life cycle analyses, which aggregate the systemic impacts but do not establish a direct relationship between the structure or quality of cycling and its impacts. Such relationships cannot be established

[16] Recycling is not always the preferred option, as in the biopolymers case, although recycling always has a reduced environmental impact (at least in some aspects) compared to the landfill option.

[17] This is an ideal situation assuming that no losses occur during production, use and recycling.

by using LCA because LCA does not reveal the internal structure nor dynamics of the studied system, it rather focusses on aggregating and allocating the different environmental impacts under assessment.

Production engineering and Industrial Ecology have developed simple recycling indicators to quantify the amount of recycled flows and their proportion compared to other relevant flows. Thus, the focus of the indicators is process-based to understand the amount of resources used or saved at the level of the sector using the resources — not at system level. These indicators are reviewed below in section 2.6.2.

On the other hand, ecological analysis has developed more complex metrics/indicators using systemic approaches because it was noted that cycling had important indirect effects on the ecosystem behaviour. A recent summary explaining the systemic effects and the development of indicators and methods to study cycling within ecosystems can be found in Allesina and Ulanowicz (2004):

> "Energy and matter cycle in ecosystems. This phenomenon, which has been widely examined in literature (see for example Ulanowicz (1983); Patten and Higashi (1984); Patten (1985); Essington and Carpenter (2000); Christian and Thomas (2003), is one of an ecosystem's most important features, because it affects the residence time of nutrients (Herendeen, 1989), acts as a buffer for fluctuations in energy supply (Loreau, 1994), augments stability (DeAngelis et al., 1989), and greatly affects ecosystem functioning.
>
> Although the presence of trophic cycles was discovered early in ecological studies (Hutchinson, 1948), the first method for actually quantifying the amount of cycling matter/energy was not introduced until the end of the 1970s, by Finn (1976), in the context of ecological network analysis (ENA) (Baird and Ulanowicz, 1989; Christensen and Pauly, 1992; Fath and Patten, 1999). What became known as Finn's cycling index (FCI) accounts for the percentage of all fluxes that is generated by cycling, and has been applied in a wide range of ecological studies (e.g. Bodini and Bondavalli (2002); Christian and Thomas (2003); Fath (2004); Heymans et al. (2004); Manickchand-Heileman et al. (2004)).
>
> Finn's seminal work has been extended by Patten and Higashi (1984), to incorporate biomass storages into the computation via Markovian techniques. The computation was further improved by Han (1997) through his definition of cycling matrix; in a similar fashion, Szyrmer (1984), expressed the cycling contribution of each compartment to the "total flow". Yet another approach was initiated by Ulanowicz (1983) who devised a procedure to extract cycled

> flows from the network and compare their activities with the remaining unidirectional flows."

The indicators mentioned in this summary and some others are reviewed in sections 2.6.2 and 2.6.4.

Ecosystems and industrial systems are similar since they are both dissipative systems. Industrial Ecologists have used this similarity to port the analytical tools developed in trophic food web analysis to study cycling in industrial systems (Suh, 2005; Bailey et al., 2004a,b, 2008). Using the same analytical tools to model both ecological and economic systems stems from the links established on how ecosystems evolve and their relevance for human ecology (Odum, 1969, 2007), which led to the analysis of the energy and material flows within societies from an ecological perspective (Odum et al., 1987; Odum, 2007). Then, this approach has also been embraced by the Industrial Ecology field which tries to understand the links between industrial activities and ecology (Ayres and Ayres, 2002), either at process-specific levels but also at system level (e.g. by using IOA (Suh, 2008) to analyse industrial interactions). Industrial Ecology has also identified cycling as a key systemic component to reduce resource consumption and emission generation (recall section 2.5.1.1).

The metrics reviewed below are only physical measures related to (re)cycling. Non-physical measures are not considered since the focus is on the physical structure of the economic system.

2.6.2 Simple recycling metrics[18]

2.6.2.1 The virginity index

Wernick and Ausubel (1995) developed several metrics to understand the material use within the economic system. Some of these measured a particular aspect of the (re)cycling processes, aiming to assess the material efficiency or "cyclicity" of the economic system.

The metric is defined as

$$\text{Virginity index} = \frac{\text{Virgin Material Input}}{\text{Total Material Input}} \tag{2.30}$$

[18]The review of simple recycling metric is strongly based on Bailey et al. (2004a,b) and Bailey et al. (2008).

2.6.2.2 The recycled content

The virginity index can be converted to the recycled content metric, which is more used to characterise industrial material flows, e.g., to indicate the (recycled) composition of a product (Bailey et al., 2008). Since Total Material Input = Virgin Material Input + Recycled Input,

$$\text{Recycled content} = \frac{\text{Recycled Input}}{\text{Total Material Input}} = 1 - \text{Virginity index} \tag{2.31}$$

2.6.2.3 The recovery rate

Wernick and Ausubel (1995) also thought about a metric capturing the rate at which a material is recovered after consumption It is defined as

$$\text{Recovery rate} = \frac{\text{Materials recovered after consumption}}{\text{Total material consumption}} \tag{2.32}$$

2.6.2.4 The recycling rate

While recovery rate focusses on post-consumer recycling (i.e. after the use of final products by final consumers), the recycling rate aims to capture the recycling of all types of material flows, i.e. of new and old scrap[19] (USGS, 2001).

$$\text{Recycling rate} = \frac{\text{Materials recovered for recycling}}{\text{Total material consumption}} \tag{2.33}$$

This measure is used by trade or statistical organisation to assess the overall level of recycling within a given industry (Bailey et al., 2008).

2.6.2.5 The fraction recycled

Ayres (1994b) developed the *fraction recycled* metric to describe the current recycling practices compared to best available practices. Therefore this metric is subject to different assumptions which may make it a controversial metric.

$$\text{Fraction recycled} = \frac{\text{Materials recycled}}{\text{Materials potentially recycled}} \tag{2.34}$$

[19] According to USGS (2001), new scrap is “produced during the manufacture of metals and articles for intermediate and ultimate consumption” and old scrap “includes but is not limited to metal articles that have been discarded after serving a useful purpose”

2.6.3 Systemic cycling metrics

The systemic cycling metrics stem from ecological studies of trophic food chains using the IOA framework, a field opened by the seminal work of Hannon (1973a). Some metrics are derived using network analysis methods, usually based on graph theory which can in turn be applied to Input-Output Analysis since IOTs are special types of graphs — namely directed graphs or digraphs (Patten (1985) establishes formally a parallelism between ecological IOA and graph theory).

Suh (2005) compared ecological and economic IOA methods. The nomenclature is different but the only difference is that ecological IOA uses input-driven models (also known in economics as the Ghosh model (Ghosh, 1958; Miller and Blair, 2009)) since the trophic food webs respond to the primary inputs fed to the system and the economic systems modelling use output-driven models (also known as the Leontief model (Leontief, 1941; Miller and Blair, 2009)) since the overall production responds to the final output demand.

Reading ecological and economic IOA literature can be confusing since they sometimes use the same notation to denote different system components and they use different names to denote the same operational components. The main ecological components are described next with their corresponding term in economic IOA. This equivalence can be established by comparing the notation in Hannon (1973b) and Finn (1976) to Miller and Blair (2009):

- (Total) inflows = total inputs
- (Compartment) throughflow or throughput = (Sectoral) total output (or input)
- Export = final outputs
- Respiration = disposals to nature (in the case of Physical Input-Output Tables)
- The economic "technical coefficient matrix" has no specific name in ecological IOA. Sometimes, the ecological "technical coefficient matrix" is defined by adding one or two prime marks[20] depending whether it is a input-driven or output-driven determined matrix.
- Transitive Closure Matrix = Leontief (or Ghosh) inverse matrix
- Total System Throughput (TST) = would correspond to the sum of all sectoral total outputs

In the following review, the equivalent concepts and/or notation to economic IOA will be provided in straight brackets. The economic notation will follow the one in Miller and Blair (2009).

[20]Some authors use asterisks instead of prime marks (Suh, 2005).

2.6.3.1 The (Finn) Cycling Index

Finn (1976) devised a cycling index (CI) considering all cycling happening within the observed system, which was the seminal work enabling the study of cycling systemically in ecology; it was later known as the Finn Cycling Index (FCI) (Allesina and Ulanowicz, 2004).

Finn (1976) starts his paper by exploring the concept of Average Path Length ($\overline{APL}$), which he defines as the average number of compartments through which inflow passes. In page 368, he formally relates the APL measure to the Total System Throughflow (TST) [sum of all total inputs (or outputs)] and total inflows [sum of all primary inputs].

Then, he assumes that TST and $\overline{APL}$ have a straight through and a cycled portion:

$$TST = TST_s + TST_c \tag{2.35}$$

$$\overline{APL} = \overline{APL}_s + \overline{APL}_c \tag{2.36}$$

Then, he defines a cycling index as

$$CI = \frac{\overline{APL}_c}{\overline{APL}_s} = \frac{TST_c}{TST_s} \tag{2.37}$$

The CI "denotes how many times further than the straight throughflow path length an average unit of inflow travels because of cycling" (Finn, 1976). In other words, it represents the total amount of cycling over the total amount flows traversing the system.

However, the issue still remains how to find either TST_c or TST_s for any arbitrarily complex system. The solution lied in the examination of the transitive closure matrix (equivalent to the Leontief inverse matrix) since it captures all direct and indirect systemic interactions, and thus all cycling ones. He argued that the diagonal elements the transitive closure matrix indicate the amount of cycling passing through each specific sector. In particular, the amount exceeding one in the diagonal elements reveal the amount of cycling per unit of output (Finn, 1976, pg. 369); thus,

$$(\mathbf{I} - \mathbf{Q})^{-1}_{ii} = \mathbf{L}_{ii} = 1 + [\text{cycled flow in } i \text{ due to one unit of final output from sector } i] \tag{2.38}$$

By applying this idea to the whole Leontief inverse — i.e. by adding the excess of one of each diagonal element multiplied by the corresponding outflow, he calculates the total system throughflow that constitutes cycling.

Within Industrial Ecology, Suh (2005), Bailey et al. (2004b) and Bailey et al. (2008) reviewed how to apply this indicator to economic and industrial systems.

2.6.3.2 The Return Cycling Efficiency

According to Bailey et al. (2004b), the return cycling efficiency of a given compartment k (RE_k), is the percent of flows that are cycled in that compartment, and can be defined as

$$RE_k = \frac{n^*_{kk} - 1}{n^*_{kk}} = \frac{n^{**}_{kk} - 1}{n^{**}_{kk}} \tag{2.39}$$

where, n^*_{kk} and n^{**}_{kk} represent the diagonal elements of an input and an output transitive closure matrix (i.e., corresponding to the diagonal elements of a Leontief or Ghosh inverse matrix). The equivalence holds since these matrices are similar (Miller and Blair, 2009, chap. 12.1.2).

According to Bailey et al. (2004b), using RE_k and the total process throughflow T_k [equivalent to x_k], the TST_c can be defined as follows:

$$TST_c = \sum_{k=1}^{n} RE_k T_k \tag{2.40}$$

Using this idea, Bailey (2000) decomposed this metric into RE_c and RE_p, called "consumption" and "production" cycling efficiencies. These provide the same information as RE_k independently for consumption and production processes.

2.6.3.3 Eigenvalues

A different approach to study cycling is to determine the presence and strength of structural cycles (Fath and Halnes, 2007).

It is based on the study of the eigenvalues of the adjacency (or connectance) matrix[21]. The cycling is related to the maximum eigenvalue of the adjacency matrix from which three situations are possible:

1. maximal eigenvalue is zero: no structural cycling happens;
2. maximal eigenvalue is below one: weak cycling exists, i.e. the number of pathways between nodes [sectors] does not increase geometrically with increasing path length between these nodes;

[21] In graph theory, an adjacency matrix is a binary representation of the system connections. It could be understood as a filter of the inter-sectoral matrix, whereby non-null values become 1 and null-values remain null.

3. maximal eigenvalue is above one: strong cycling exists, i.e. the number of pathways between nodes [sectors] increases geometrically with increasing path length between these nodes.

However, according to Fath and Halnes (2007): "the eigenvalue does not measure the quantity of flow; and therefore, differs from the Finn (1976) cycling index, which is a measure of cycled flow".

2.6.4 Structural decomposition of the inter-sectoral cyclic component of a dissipative system: the Ulanowicz algorithm

So far, the method suggested by Ulanowicz (1983) is the only one suggesting an algorithm to identify and quantify — to decompose — explicitly the inter-sectoral flows of a system into its cyclic and acyclic components.

The Ulanowicz (1983) algorithm (also explained in Ulanowicz and Kay (1991)) can be divided in two sub-algorithms: a first one identifying all simple cycles happening within the intersectoral matrix and a second one assigning a specific weight to each identified cycle. To find all simple cycles, Ulanowicz choose a graph theory backtracking search algorithm devised by Johnson (1975) — the quickest of its type (Mateti and Deo, 1976). Then, to allocate a weight to each simple cycle, he devised an iterative sub-algorithm distributing the weight of the weakest (i.e. smallest) link of all cycles — which is the cycling bottle-neck — amongst all cycles passing through this link.

The Ulanowicz (1983) algorithm can be summarised as:

1. Identify all simple cycles of the system (i.e. cycles not repeating any node).
2. Identify the weakest link of every cycle (i.e. the link with the smallest flow/weight).
3. Identify the weakest link amongst the previously identified weakest links.
4. Allocate its value among all cycles in which it is involved — also called a nexus — according to the circuit probability of accomplishing each cycle[22] normalised by the sum of circuit probabilities.
5. Subtract the allocated weight of the cycles of the nexus from the intersectoral matrix. (This breaks all cycles of the nexus since the weakest link of the nexus is zeroed).
6. Iterate over the remainder array until all cycles are removed.

[22] The circuit probability is the probability of a particle fulfilling the circuit, i.e. the cycle. Thus, the circuit probability of a cycle is the product of the output probabilities of getting from a link to the next link of the cycle until completed. The output probability to go from a to b is defined as the output weight of getting from a to b (z_{ab}) divided by the total output of a ($\underline{x}_a$).

The self-cycles — the cycles involving a single sector — are treated separately to avoid unnecessary calculations since their decomposition is trivial: they are the diagonal elements of the IOT.

When finished, the original system — i.e. the intersectoral matrix[23] $\mathbf{Z}$ — is decomposed into the *cyclic matrix* $\mathbf{Z}^c$ embodying the cyclic flows within the system and the *acyclic matrix* $\mathbf{Z}^a$ which, according to (Ulanowicz, 1983), it embodies the acyclic flows within the system, as follows:

$$\mathbf{Z} = \mathbf{Z}^c + \mathbf{Z}^a \tag{2.41}$$

2.6.5 Discussion and gaps in the understanding and study of the cyclic structure of the economic system

2.6.5.1 Structural characterisation of cycling

As seen in section 2.6.2, simple recycling metrics (used traditionally to quantify industrial recycling) focus on the (re)cycling affecting a specific process and thus they are built using flows ratios related to the same process. For instance, the recycled content — the recycled inputs over the total inputs — and the recovery rate — the material recovered after consumption over the total material consumption — inform on the cycling flows regarding a specific process (Bailey et al., 2008).

The simple metrics quantify how much cycling is happening only at the point of the measure, but do not provide information on how the cycling happens within the system (e.g. the flow which is recycled might involved many inter-sectoral loops or only a single one) nor capture other effects associated to cycling. This observation is expected because of the way the indicators are built: they all use measures either related to the inputs/outputs of the process or to the total input/outputs of the system, therefore they cannot provide information on the distribution of cycling within the system.

Turning to the systemic cycling metrics:

The (Finn) Cycling Index (Finn, 1976) does not explicitly reveal the structure of the cycles, it derives an aggregate index capturing the total amount of inter-sectoral cycling going through the system. The indicator is based on TST_c, which, according to Finn explanation, represents a measure of the total inter-sectoral cycling, but not the inflows [primary resources] nor respiration [emissions] associated to cycling.

[23]In this thesis, upper case, bold letters denote matrices; lower case, bold letters denote vectors; and lower case letters denote scalars.

Fath and Halnes (2007) develops a method based on analysing the eigenvalues to assess whether the type of cycling happening within a given system is weak or strong, but does not provide an explicit measure of the amount of cycling within the system.

So far, Ulanowicz (1983) has developed the only method that reveal the disaggregated structure of cycling but *exclusively* for intersectoral flows, i.e. he did not associate primary resources nor emissions to the cycling component nor to the acyclic component. Therefore, assuming that the Ulanowicz algorithm and assumptions (Ulanowicz, 1983) are correct, the Ulanowicz algorithm will need to be extended in order to calculate the primary resources and emissions associated to the inter-sectoral cycles.

Since the chosen analytical framework to analyse the physical structure of the economic system is IOA, it is important to note that IOA is the core framework used to extract systemic indicators associated to cycling. In particular, the transitive close matrix [the Leontief or Ghosh inverse matrices] are the primary metric that allow researchers to obtain the amount of cycling per unit of output (Finn, 1976) and the eigenvalues, which characterise whether cycling is weak or strong (Fath and Halnes, 2007). Also, the methodology developed in Ulanowicz (1983) is based using network analysis on the IO framework.

Therefore, only two methods have been developed so far to *explicitly and directly* identify and quantify the cyclic structure systemically: the Finn Cycling Index (Finn, 1976), which provides an aggregate measure of all inter-sectoral cycling happening within a system, and the Ulanowicz algorithm (Ulanowicz, 1983), which identifies and quantifies all inter-sectoral cycles happening within a dissipative system such as a trophic food web[24]. More recent reviews in ecological analysis (Ma and Kazanci, 2014) and in industrial ecology (Bailey et al., 2008) also find that only these two methods/indicators are available to quantify cycling systemically.

Characterising the complete structure of cycling is key since (re)cycling has been identified as a key feature for a more materially sustainable economic system (see section 2.5). Since a method to fully characterise the cyclic structure of a dissipative system is still lacking and, in particular, of the economic system, the main objective of thesis is to develop the concepts and method to identify and quantify the different structural components associated to the cyclic structure (and any other sub-structural component required for that particular decomposition). In chapter 4, the theoretical foundations of the Finn Cycling Index (Finn, 1976) and the structural decomposition suggested by Ulanowicz

[24]Since, from a material flow perspective, the economic system is also a dissipative system where its sectors dissipate part of the material flows directly to the environment (as emissions), the methods developed to study dissipative systems such as trophic food webs can also be applied to study the physical metabolism of the economic system.

(1983) will be reviewed to develop a method to identify and quantify the complete cyclic physical structure of the economic system.

2.6.5.2 Systemic structural analyses and systemic impact assessment of cycling

The relationship between cycling and other systemic properties has been weakly characterised in ecology. While the influence of cycling of relevant systemic properties has been identified (Herendeen, 1989; DeAngelis et al., 1989; Loreau, 1994), a direct explicit relationship between the cyclic structure and these components has not been established. Finn (1976) suggested that the Cycling Index could help understanding the stability and productivity of ecosystems. However, later studies (Christian and Thomas, 2003; Heymans et al., 2004) usually use the FCI as a proxy for amount of cycling, which is then used for comparative purposes of the studied systems, and used as an explanatory variable rather than to characterise directly specific system behaviour or properties.

Bailey et al. (2004b) discussed the relationship between cycling and the environmental impact of the system by using cycling as a proxy for the time materials spend within the system. They imply that the more time materials spend within the economy, less resources are required and emissions are generated. They use the Finn Cycling Index (FCI) and the Path Length (PL) as indirect measures (proxys) of the time spent within a system to analyse the environmental impact of the system. However, the relationship between the FCI, PL and residence time is not formally established.

Additionally, Bailey et al. (2004b) discuss the different environmental impact associated to "consumption" and "production" cycling. They argue that increasing [residence] time spent within consumption is beneficial from an environmental perspective; in particular, the environmental objective "is to increase the material cycling to consumption while decreasing material cycling in production". They also refine their understanding of production cycling: they suggest that increasing it is beneficial when recycling materials that would be discarded, but decreasing it is beneficial if more materials are transformed into final products directly (instead of being involved in cycling). However, there is no formal demonstration of the reason underlying this statement.

Modelling and assessing the effects of cycling in industrial systems has used heterogeneous system types and boundaries that do not necessarily correspond to the economic system behaviour. In particular, Bailey et al. (2008) represent the economic system as non-dissipative system and only for special cases whereby the system produces only a single final product. However, the economic system is dissipative and complex (i.e. produces several final products simultaneously). Also, Bailey et al. (2004b) uses closed models from an IO perspective, i.e. consumption is endogenous in the system boundary. While this does not constitute an analytical limitation, it conflicts with the aim of developing a more generic analytical framework where production can be studied in isolation (as it is in traditional IOA).

To sum up, there is no formal theoretical understanding of how the cyclic structure affects the system behaviour or properties. In particular, the relationship between cycling and environmental impacts of the economic system are still poorly understood. This might be due to the fact that, as pointed out in the previous sub-section (2.6.5.1), there is no explicit characterisation of the full cyclic structure, which hinders the possibilities to establish such relationships. In the context of a transition towards a more sustainable economic system, establishing direct relationships between its cyclic structure and its environmental impact would be of great help. In particular, it would be useful to understand how cycling affects the levels of resource extraction and emission generation, and of the overall resource efficiency of the economy. Therefore, after developing a method to identify the full cyclic structure in chapter 4, it will be sought in chapter 5 to establish direct relationships between the cyclic components of the structure and some properties of the system (e.g. its resource efficiency or total emissions generated due to cycling); also, indicators to capture these impacts will be developed to analyse the structural impact of cycling.

Also, current system definitions and IO methods used to model cycling in the economic system have ad-hoc specifications which do not represent how the system works or are not compatible with more general IO frameworks. Therefore, it would be useful to develop the method to identify and quantify the full cyclic structure using using a generic framework representing how the economic system works (i.e. as a dissipative system) and in the traditional open model approach (i.e. with an exogenous final demand, so that production can be independently analysed from consumption). This need is aligned with the previous objective of further developing the theoretical understanding of how to use Physical Input-Output Tables for structural analyses (see section 2.4.5), which is developed in chapter 3.

2.6.5.3 Cross-check of previous methods

Although both methods quantify the level of inter-sectoral cycling, a link between the Ulanowicz method (Ulanowicz, 1983) and the (Finn) Cycling Index (Finn, 1976) has never been suggested. However, different results are found when comparing the cycling calculated with the FCI method and Ulanowicz' algorithm. For instance, when applying these methods to table 3.4 (the dataset used as numerical example throughout this research, described in section 3.2.2.3), Ulanowicz' method gathers the cycles represented in equation 4.2 (page 133) which, added, result in 1267 millions of tons of materials involved in cycling. This figure should equal TST_c (which is used to calculate the FCI), since TST_c equals the total inter-sectoral cycling flows happening within the system (Finn, 1976). However, the total cycling (TST_c according to Finn's notation) for the same PIOT is, according to equation 2.38: $TST_c = 3.124 \cdot 20 + 2.256 \cdot 657 + 0.987 \cdot 67 = 1613.1$. The difference between both measures raises the question whether these methods (or which one of these methods) quantify the cycling structure in an appropriate manner. Therefore, the first thing to do is to establish which method is gathering correct results; section 4.2 in chapter 4 will review the theoretical foundations of both methods to understand this inconsistency.

2.6.5.4 Complementing other structural analysis methods

The identification of the full cyclic structure might complement previous structural analysis methods. In particular, revealing the full cyclic structure might be helpful to identify important technical coefficients (i.e. system flows), e.g. which have higher connectivity to the system through high amounts of cycling. Such type of approach would be different than the one suggested in section 2.4.5.3 because traditional methods to assess the relevance of technical coefficients test the impact of different coefficients without knowing a priori whether the tested coefficient is important. In this case, the understanding of the cyclic structure might help pinpointing important coefficients a priori plus provide an explanation for the relevance of these coefficients through the understanding of how they contribute to the cyclic structure (and related systemic impacts).

2.6.6 Summary

Being able to identify the cyclic structure of the economic system is vital to inform industrial and technology policies targeting the implementation of a closed-loop, circular economy. However, according to the review in this section, current cycling indicators of the industrial system are either process-based and or are very aggregated and mask the structure of cycling (e.g. the Finn Cycling Index (Finn, 1976)). In fact, the cyclic structure of a dissipative system has only been characterised partially (Ulanowicz, 1983), i.e. the resources and emissions associated to the cyclic structure have not been explicitly found, masking the relationship between cycling and resource use and emission generation. The methods developed by Finn (1976) and Ulanowicz (1983) are the only ones developed so far to identify and quantify explicitly the cyclic structure[25] in ecological systems (Ma and Kazanci, 2014) and in industrial systems (Bailey et al., 2008).

Also, since the previous methods have not fully characterised the cyclic structure, they are unable to account for the systemic effects associated to cycling (e.g. the emissions associated to the cyclic structure). Similarly, the systemic effects of cycling, while empirically inferred through LCA, have not been theoretically related to the system structure because the cyclic structure has never been fully characterised. So, to develop a sound theory behind the circular economy concept, the theoretical relationship between the cyclic structure and the resource extraction and emission generation of the economic system, i.e. its resource efficiency and emission intensity, should be established.

Since shifting towards a cyclic structure seems to be a systemic solution to mitigate environmental degradation (i.e. resource use and emission generation), this research focusses on characterising the cyclic structure of the economic system and linking it theoretically to the resource efficiency and emission intensity of the system to inform policies aiming to induce such shift. In particular, it should be determined whether all types of cycling are equally beneficial and whether different cycling structures have different systemic effects. In this research, cycling will be analysed from a static perspective, i.e. considering the different systemic effects associated exclusively to the structure. The dynamics of a system are the result of the interaction between the structure and the time-dependent variables. Therefore, the (static) systemic effects of the structure need to be well understood before engaging in a dynamic study.

However, before being able to develop specific tools and decompositions to explore the cyclic structure of the economy, it is required to understand how to use conventional input-output methods to analyse the physical structure of the economy. Chapter 3 is interested in developing such understanding.

[25] Another method relating the algebraic properties of the physical structure to its cyclic structure by analysing the structure eigenvalues and eigenvectors has been developed (Fath and Halnes, 2007). However, such method do not show the cyclic paths explicitly and, thus, it cannot be used to identify which flows should be targeted to alter the structure.

Chapter 3

Analysing the physical structure of the economic system

3.1 Introduction

The aim of this chapter is to understand how to analyse the physical structure of the economy by using Physical Input-Output Tables and their corresponding Input-Output models. This might seem a trivial task given the large body of literature on input-output models. However, as reviewed in section 2.4.2.1, this is not the case for Physical Input-Output Tables (PIOTs) because only a few papers have discussed how to apply input-output models to PIOTs, and different results have been found using the same table (Dietzenbacher et al., 2009). Thus, it is unclear why such different results are found and a clear recommendation on which model to use is still missing.

The new System of Environmental and Economic Account (UN et al., 2014b) relies almost exclusively on the Physical Supply and Use Table framework (which in turn can be used to produce PIOTs) to compile the data about the material flows induced by the economy. However, the official applications suggested for this framework only review conventional IO models and methods based on EE-MIOTs and hybrid-IOTs (UN et al., 2014a). This is most probably due to the fact that these types of applications are currently well understood and broadly used (see section 2.4.2.1). However, paradoxically, there is no mention how to use or analyse PIOTs even if PIOTs is the framework put forward by the UN et al. (2014b) themselves.

The lack of applications of the PIOT framework was previously noted by Hoekstra (2010) and pointed as a reason for the reduced interest in the framework. However, the lack of applications is most probably due to the lack of understanding of the input-output models suitable to operate and analyse PIOTs, since previous literature has not been conclusive about which input-output models or methods are suitable for that purpose. Section 3.2 of this chapter aims to fill this gap.

In particular, in section 3.2.1, the PIOT framework is reviewed in depth and the analytical differences between conventional MIOTs and PIOTs are highlighted. It is concluded that only two methods are appropriated to calculate the primary resources and emissions associated to any given final demand. Then, these two methods are compared in section 3.2.2. It is found that, even if they gather the same correct results, they gather different structures (i.e. different Leontief and technical coefficients matrices). At this point, it is known which IO methods/models can be used with PIOTs but it is unclear how to analyse the physical structure of the economic system, since each method reveals a different structure. Therefore, in section 3.2.4, a theoretical explanation for the different structures are provided together with a numerical example based on a backward linkage analysis.

Additionally, as discussed in section 2.4.5, the traditional Input-Output Analysis (IOA) methods for structural analysis are limited in scope in the sense that they provide aggregate indicators of the intersectoral structure. So, a more disaggregated analysis tool could provide further insights into the structural relationships between the system's components and, in particular, on the structure of the intersectoral flows. For that purpose, in section 3.3, a new visualisation tool enabling researchers to perform disaggregated structural analyses and identify intersectoral patterns visually is developed.

To summarise, this chapter develops the theoretical understanding currently required to analyse the physical structure of the economy using the Input-Output framework: first, by explaining which methods can be used to find the primary resources and emissions associated to PIOTs (and discarding inexact methods) and, then, by explaining which method can be used to perform structural analyses (only one of the two previously considered methods reveals the actual physical structure of the economy). Additionally, this chapter develops a tool to perform disaggregated structural analyses visually.

This chapter is a necessary step towards the main aim of the thesis — to identify how to improve the resource efficiency of the economy by altering its physical structure — because it needs to be well understood how to use input-output models to analyse the physical structure before being able to develop more sophisticated analytical methods. In particular, in chapter 4, the PIOT framework is used to identify the cyclic structure of the economic system using network analysis, for which some calculations of the PIOT are required and, thus, it is required to have a clear understanding on which input-output models can be applied to PIOTs.

Also, by mastering the input-output methods that can be applied to PIOTs, conventional analyses can be performed on PIOTs, as it will be illustrated in chapter 6. The use of the circular diagrams developed in section 3.3 will also be illustrated in chapter 6.

Note that this chapter is mostly methodological, although an in-depth review about the PIOT framework is provided in section 3.2.1 and some results are provided in section 3.2.4 to illustrate how to perform a structural analysis on a PIOT. The mathematical notation follows the one in Miller and Blair (2009), i.e. lower case letter for scalars (e.g. z_{ij}), bold lower case letters for vectors (e.g. $\mathbf{f}$) and bold upper case letters for matrices (e.g. $\mathbf{Z}$). Finally, in this chapter, the term *disposals to nature* refers to all material flows that the economy releases back to the environment and it can be used interchangeably with the terms *waste* and *emissions*.

3.2 Using Input-Output Analysis

3.2.1 The PIOT framework

This subsection first reviews the relationship between the different types of IOTs and the different types of IO models; then, the accounting rules for PIOTs are examined and, finally, the different models applicable to PIOTs are reviewed.

3.2.1.1 On input-output tables and input-output models

An Input-Output (IO) model is the set of equations that relate the different components of a specific Input-Output Table (IOT) by using certain assumptions. Leontief (1941) devised the first IO model by assuming that each economic process requires an amount of inputs linearly related to the total amount of outputs produced. This first model is also known as an *output-driven* or *demand-led* model because economic activity is driven by the production of final products. The Leontief model is the starting point for other models such as the pollution abatement model, environmentally-extended models and dynamic models (Miller and Blair, 2009).

IOTs are a consistent accounting framework that represents the flows (not the stocks) within a given system: e.g. the monetary flows between the economic sectors compiled in a Monetary IOT (MIOT), or the physical flows between the economic sectors represented in a Physical IOT (PIOT). All IOTs are based on the accounting principle that "what comes in, goes out". In MIOTs, this reflects the double entry bookkeeping principle; in PIOTs, the mass balance principle.

However, not all IO models can be applied to all IO tables; in fact, IO models are tailored to the specificities of each IOT. For example, the pollution abatement model requires a special table with an extra row representing the pollution generation and an extra column representing the pollution abatement sector (Miller and Blair, 2009, chap. 10.5). Thus, an IOT can only be analysed with IO models that match the underlying relationship between the elements of the table and the same holds for PIOTs.

3.2.1.2 Review of constructed PIOTs

PIOTs record *all*[1] material flows occurring within an economy — goods and emissions associated with the production of goods — so, by definition, PIOTs differ fundamentally from other IOT types (MIOTs, hybrid-IOTs and environmentally-extended MIOTs) for two reasons: firstly, because they represent flows without market value — emissions; and secondly, because PIOTs account for the production of by-products — emissions and waste — that are disposed to nature and accounted as final output in the IO context. PIOTs are unique in their capacity to include those disposals to nature and this section is interested only in the emissions and wastes that are disposed to nature (which cause the loadings into the BGCCs discussed in section 2.2), not in the (currently minor) part that is re-used within the economy and treated as recycled by-products. From now on, both the terms *emission* and *waste* refer to emissions and wastes disposed to nature unless otherwise stated, and can be used interchangeably with the term *disposals to nature*.

The first difference between a PIOT and other types of IOTs implies that the former are the only IO accounting framework that permits analysis of the physical structure of an economy, because they include *all* physical flows, whether marketed or not. The second difference leads to methodological issues because traditional IOTs produce only a single final output[2] — a final good — while PIOTs produce at least two different but related final outputs — final goods and disposals to nature. By definition, PIOTs represent the simultaneous production of intermediate and final goods together with the emissions and wastes generated during their production and this constitutes their analytical advantage: PIOTs directly relate emissions to the production of goods. On the other hand, this

[1] It is possible to construct PIOTs without emissions by including only the fraction of primary resources embedded in the intermediate and final production. However, such PIOTs are a truncated representation of the material flows induced by production. So, in this thesis, only PIOTs including emissions are considered.

[2] Traditional IOTs include a single final output: final goods, which might either be homogeneous or heterogeneous, depending on the construction of the IOT. The use of IO models usually imply the simplifying assumption of homogeneous goods.

specificity impedes the direct use of traditional allocation techniques[3] and IO models in a PIOT, as discussed in section 3.2.1.3.

In the following paragraphs, it is examined how MIOTs are constructed to compare them to PIOTs and to highlight the difference that impedes the application of conventional IO models to PIOTs. The algebra notation follows the one in Miller and Blair (2009): lower case letters are scalars, bold lower case letters are vectors and bold upper case letters are matrices.

MIOTs represent the flows of goods and services between economic sectors in monetary units. Their structure consists of a 1st quadrant representing the primary inputs of the system: the value-added vector $\mathbf{v}'$; a second quadrant called the inter-sectoral matrix $\mathbf{Z}$ registering the exchange of goods between the sectors of the economy, also called intermediate production or demand; and a 3rd quadrant containing final goods $\mathbf{f}$, also called final demand (see table 3.1). Traditional IOTs only contain a single final output: final goods $\mathbf{f}$.

	Sector 1 … Sector n	Final demand	Total outputs
Sector 1			
⋮	$\mathbf{Z}$	$\mathbf{f}$	$\mathbf{x}$
Sector n			
Value added	$\mathbf{v}'$		
Total inputs	$\mathbf{x}'$		

Table 3.1: Structure of an IOT with a single final output $\mathbf{f}$ representing a traditional MIOT. All components are in monetary units.

A PIOT can be intuitively constructed following the same structure by using the principle of mass conservation ("the materials that come in, go out") and using physical units instead of monetary ones. Thus, PIOTs also have three quadrants representing similar flows (see table 3.2): the 1st one consists of the total amount of primary resources required by the economy $\mathbf{r}'$, the 2nd quadrant relates the material exchanges between the sectors of the economy $\mathbf{Z}$, and the 3rd represents the final outputs of the system: the final goods for consumption $\mathbf{f}$ and the corresponding sectoral emissions disposed to nature $\mathbf{w}$ due to *total* sectoral production (both intermediate and final). The disposals to nature can represent different material flows, depending on the materials traced: waste, pollution and even non-pollutant emissions. Thus, PIOTs are different from conventional IOTs since they produce at least[4] two final products, $\mathbf{f}$ and $\mathbf{w}$, one related to the other since

[3] Allocation techniques of secondary production using Supply and Use tables (SUTs) cannot be applied to disposals to nature since they are not re-used as secondary production within the economy but directly disposed *outside* the economy.

[4] In section 3.2.5, it is shown how to analyse PIOTs with more than two final outputs.

the generation of the disposals to nature depends on the amount of intermediate *and* final products produced. Hence, such IOTs include *multiple related final outputs*, all of which are included in its total output. To highlight this difference relative to traditional IOTs, the total output of an IOT with *multiple related final outputs* is indicated as $\underline{\mathbf{x}}$.

	Sector 1	...	Sector n	Final demand	Waste	Total outputs
Sector 1						
⋮		$\mathbf{Z}$		$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Sector n						
Resources		$\mathbf{r}'$				
Total inputs		$\underline{\mathbf{x}}'$				

Table 3.2: Structure of an IOT with two final outputs (final goods $\mathbf{f}$ and emissions $\mathbf{w}$) representing a PIOT. All components are in physical units.

Several countries followed this structure to build their own PIOTs: Germany (Statistisches Bundesamt, 2001), Denmark (Pedersen, 1998, 2004, 2005) and Italy (Nebbia, 2000). However, despite sharing the same accounting structure, each PIOT represented different economic sectors and materials according to the scope of the project and the available raw data on physical accounts. The German and Danish PIOTs were developed by the corresponding statistical offices and based on detailed information on the inter-sectoral transactions of the products derived from previously compiled physical supply and use tables (PSUTs). They achieved finer detail in terms of sectoral and material disaggregation than the Italian PIOT, which was developed using aggregated data.

The nature of the material flows represented in each table varies: the Danish table originally focused on product flows, complemented by estimates for wastes and emissions (Pedersen, 1998), and was later extended to trace the generation of waste and emissions with greater accuracy (Pedersen, 2004, 2005). The Italian PIOT captures the emission of stocks-in-use; and the German PIOT disaggregates waste into four types, including recycling flows.

PIOTs can record different material elements or aggregates of those elements. The Italian PIOT is the most aggregated, presenting all materials in a single table. The Danish PIOT is in fact a set of 8 tables representing different material aggregates, e.g. construction materials (such as sand, gravel or cement) or animal and vegetable products. The German PIOT is a wider framework including several tables with all material elements used by the economy, even including oxygen for combustion and respiration of humans as well as other biomass.

The full potential of PIOTs in terms of material accounting is exemplified by Pedersen (1998). He first constructs eight PIOTs for aggregate materials, which are then further aggregated into another PIOT to represent all material flows of the Danish economy. To illustrate other accounting possibilities, he also constructs a PIOT for a single material (nitrogen) and another for a transverse goods category — packaging — that includes different types of material such as paper, cardboard and plastics. The fact that a PIOT can represent a single material allows environmental impacts to be directly related to those specific material flows. Hence, the previous criticism that PIOTs usually include material aggregates and are therefore not a reliable framework to trace environmental impacts (Giljum and Hubacek, 2009) does not apply in all applications.

3.2.1.3 Review of PIOT analysis

The reports which explain the construction of the German, Danish and Italian PIOTs do not mention any IO model applicable to PIOTs (Statistisches Bundesamt, 2001; Pedersen, 2005; Nebbia, 2000), nor are any models mentioned in studies examining the use of environmental accounts (Pedersen, 2003) or in up-to-date IO handbooks (Miller and Blair, 2009; Nakamura and Kondo, 2009). PIOTs were only used for descriptive purposes and not as an IOA tool because there was no IO method or model available to analyse them. It is probably due to PIOTs inappropriateness for analytical purposes that this framework lost momentum (as observed by Hoekstra (2010)) and was dismissed from environmental accounts in favour of more aggregated ones such as the Economy-Wide Material Flow Accounts (EW-MFA)[5]. In other words, constructing PIOTs is an expensive, time-consuming task which is unjustified without analytical applications.

The first attempt to calculate the final outputs and primary inputs of a PIOT for a given final demand was in 2003 and triggered a series of papers discussing the methodological issues encountered (Hubacek and Giljum, 2003; Giljum and Hubacek, 2004; Suh, 2004b; Giljum et al., 2004; Dietzenbacher, 2005; Dietzenbacher et al., 2009; Xu and Zhang, 2009). On a different note, Weisz and Duchin (2006) stated that there is no structural difference between PIOTs and MIOTs since the difference in their values stems from a change in the price vector, making both structures algebraically *similar*, i.e. sharing the same fundamental properties characterising the system. Thus, they argue that the analysis of a MIOT should provide the same results as the analysis of the corresponding PIOT. However, Weisz and Duchin (2006) analysed the properties of PIOTs without disposals to nature, which differ from the PIOTs with disposals to nature examined by the other authors. So, their statement cannot be applied to PIOTs with disposals to nature since these tables have, by definition, a different structure than PIOTs without disposals

[5]EW-MFA measures the total amount of resources that an economy directly and indirectly needs in physical units; it was originally developed as an indicator set to assess dematerialisation trends (Matthews et al., 2000) and formalised as part of the system of environmental accounts of some countries (Eurostat and European Commission, 2001; OECD, 2008a,b,c).

to nature (as revealed by their accounting relationship represented by equations 3.1 and 3.2). In other words, MIOTs are exclusively *similar* to PIOTs representing the primary resources and material flows exclusively embedded in final goods, which is not the case of the type of PIOTs under analysis in the current research.

Hubacek and Giljum (2003) used a traditional Leontief model to analyse a PIOT with disposals to nature and observed they were systematically gathering flawed results due to the different table structure of the PIOT compared to traditional IOTs. As a workaround, they devised a method for estimating the generation of emissions exogenously; this estimation method was further developed in Giljum and Hubacek (2004) but could not lead to exact results precisely because the generation of emissions was not endogenously calculated by the IO model itself (given that the total amount of emissions depends on the amount of intermediate and final goods produced).

The reason why the traditional Leontief model cannot be applied to PIOTs is as follows.

The Leontief model assumes proportionality between intermediate production $\mathbf{Z}$ and total outputs $\mathbf{x}$. This relationship is embedded in the technical coefficients matrix $\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1}$. The accounting relationship that total outputs equal intermediate plus final production $\mathbf{f}$ is formalised by

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} \tag{3.1}$$

which, merged with the previous equation, leads to $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{f}$ and $\mathbf{x} = \mathbf{L} \cdot \mathbf{f}$. This last equation relates final production to total production with the Leontief inverse matrix ($\mathbf{L}$) and implies that total outputs can be derived from knowing $\mathbf{f}$.

However, PIOTs have two different final outputs: goods and emissions, and the emissions are related to the amount of intermediate *and* final goods produced. Thus, the accounting relationship must entail the emissions. To emphasise the difference between the total outputs of PIOTs (which contain both goods and emissions) and the total outputs of a traditional IOT (which only contain goods), PIOT total output is denoted by an underline ($\underline{\mathbf{x}}$).

The accounting relationship now includes emissions $\mathbf{w}$:

$$\underline{\mathbf{x}} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} + \mathbf{w} \tag{3.2}$$

The technical coefficients matrix is redefined accordingly as

$$\underline{\mathbf{A}} = \mathbf{Z} \cdot \hat{\underline{\mathbf{x}}}^{-1} \tag{3.3}$$

which, inserted in equation 3.2, leads to

$$\underline{\mathbf{x}} = (\mathbf{I} - \underline{\mathbf{A}})^{-1} \cdot (\mathbf{f} + \mathbf{w}) \tag{3.4}$$

This last equation poses a great issue: how to calculate total outputs when only $\mathbf{f}$ is known? (one knows the initial pair $\mathbf{f}$ and $\mathbf{w}$ but not the emissions associated with any other final demand; that is why Hubacek and Giljum (2003) were forced to estimate the emissions exogenously). In short, the issue with early methods (Hubacek and Giljum, 2003; Giljum and Hubacek, 2004) is that they treat emissions as exogenous while they are endogenous, since they are generated according to the total amount of intermediate and final goods produced — i.e., emissions are the by-products of production.

The issue of having to estimate the emissions beforehand (i.e. exogenously) was solved when Suh (2004b) wrote a paper suggesting three methods applicable to PIOTs.

The first method suggested by Suh (2004b) consists of changing the units of the PIOT (from $\underline{\mathbf{x}}$ to $\mathbf{x}$) so that the traditional output-driven (Leontief) model can be applied to the altered PIOT (this transformation is analysed in detail in section 3.2.2.1). Then, Dietzenbacher (2005) used Suh's first method to calculate the waste generated corresponding to any given level of final demand; so, in this case, the emissions are endogenously calculated by considering them as negative input coefficients (section 3.2.2.1 explains the operation in detail).

The second method suggested by Suh (2004b) follows the line of the Hubacek and Giljum (2003) and Giljum and Hubacek (2004) methods, since it requires emissions to be exogenously determined. Since emissions should be endogenously determined, Suh's second method is not considered further. According to Suh himself, the third method reduces to method one. From now on, *Suh's method* refers exclusively to the *first* method devised in Suh (2004b).

Dietzenbacher et al. (2009) review all methods presented above but focus on the analysis of intensity coefficients (of land appropriation). They conclude that Suh's method "seems to be the simplest solution for treating waste disposal in PIOTs" but do not invalidate the other methods.

Finally, Xu and Zhang (2009) introduced a new multiplier — i.e. a modification of the Leontief inverse — to find the final outputs and primary inputs of a PIOT given a final demand without modifying the PIOT. However, the differences and similarities with Suh's method and the interpretation of that new multiplier remain unclear. This chapter will clarify the operation and use of both methods to analyse the PIOTs structure in the following sections. It will be the first time a structural analysis is performed on a PIOT and it will develop the theoretical understanding to analyse and interpret the results gathered by each method.

3.2.2 Operational comparison of Suh (2004) and Xu and Zhang (2009) methods

This section unifies the notation and compares the operation of the two output-driven methods applicable to PIOTs.

3.2.2.1 Suh's method

To avoid the issue posed by equation 3.4, Suh rearranges the PIOT so that "wastes are not treated as a part of the homogeneous output of a sector" (Suh, 2004b, p. 12). In other words, he subtracts the wastes from the PIOT so that only final goods remain as final outputs. Analytically, this represents a change of the units of the total outputs of the PIOT: from total outputs including emissions and waste $\underline{\mathbf{x}}$ to total outputs without waste $\mathbf{x}$, i.e. including only the final goods. Suh calls $\mathbf{x}$ *usable output* and represents it as x_1, as opposed to total output including emissions which he notes x_2. In this thesis, the change of units is formalised by the following equation:

$$\underline{\mathbf{x}} = \mathbf{x} + \mathbf{w} \tag{3.5}$$

Table 3.3 is built by subtracting $\mathbf{w}$ from the original PIOT (table 3.2), i.e. by using equation 3.5.

	Sector 1 … Sector n	Final demand	Total outputs
Sector 1 ⋮ Sector n	$\mathbf{Z}$	$\mathbf{f}$	$\mathbf{x}$
Resources	$\mathbf{r}'$		
Waste	$-\mathbf{w}'$		
Total inputs	$\mathbf{x}'$		

Table 3.3: PIOT with two final outputs ($\mathbf{f}$ and $\mathbf{w}$) transformed into a PIOT with a single output ($\mathbf{f}$) by changing the total output units from $\underline{\mathbf{x}}$ to $\mathbf{x}$.

Using the unit change (equation 3.5), equation 3.2 becomes

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} \tag{3.6}$$

which is the same as equation 3.1 and, thus, the traditional Leontief model can be applied to the transformed PIOT by defining the technical coefficients matrix as

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \tag{3.7}$$

So, thanks to the change of units, the problematic equation 3.4 becomes

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{f} \tag{3.8}$$

$$\mathbf{x} = \mathbf{L} \cdot \mathbf{f} \tag{3.9}$$

where

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{3.10}$$

The unit change transforms the PIOT which had two final outputs into a PIOT with a single final output, which allows the traditional Leontief model to be applied to the modified PIOT. The emissions vector $\mathbf{w}$ no longer appears in the model because it is output-driven and the change of units translates the emissions as negative primary inputs[6], as shown in table 3.3. The interpretation of $\mathbf{L}$ is discussed in section 3.2.4.1.

So, since emissions — a final output — have been transformed into primary (negative) inputs, emission "input" coefficients need to be defined to calculate the emissions corresponding to a given level of final demand, as suggested in Dietzenbacher (2005).

$$\mathbf{c}^w = \mathbf{w}' \cdot \hat{\mathbf{x}}^{-1} \tag{3.11}$$

The emissions associated with a given final demand are

$$\mathbf{w} = \hat{\mathbf{c}}^w \cdot \mathbf{L} \cdot \mathbf{f} = \hat{\mathbf{c}}^w \cdot \mathbf{x} \tag{3.12}$$

Equation 3.12 reveals the endogenous relationship between wastes and sectoral throughput, since $\mathbf{w}$ is a function of $\mathbf{x}$.

3.2.2.2 Xu and Zhang's method

Xu and Zhang (2009) argue in favour of keeping the PIOT framework as represented in table 3.2 because it preserves the natural input-output structure of the economy:

[6]Negative primary inputs are the mathematical representation of the output emissions given by the change of units; otherwise, primary inputs are positive.

primary resources are listed as rows (i.e. primary inputs for the system) and final goods and emissions are listed as columns (i.e. as final outputs of the system). However, by preserving the PIOT's original structure, a different technical coefficients matrix and Leontief inverse will be found.

To calculate the emissions associated to a given final demand without modifying the PIOT units, Xu and Zhang assume that the total emissions of each sector are proportional to the total output of that sector. This reasoning might not be intuitive from an output perspective but it becomes intuitive when considered from an input perspective because, by definition, total outputs equal total inputs. Therefore, from an input approach, it is intuitive to think that inputs are partly transformed into goods and partly into emissions according to a fixed ratio (which corresponds to the resource efficiency of the sector transforming the inputs into usable outputs, i.e. goods); hence, goods and emissions are linearly related to the total throughput of the sector (either seen as total inputs or outputs). In other words, PIOTs constitute a very specific type of table whereby at least two different final outputs are produced, one being a by-product of the other (disposals to nature being a by-product of the production of goods). PIOTs are thus a *multiple related final outputs* table.

This assumption explicitly relates the emission vector $\mathbf{w}$ to the total output vector $\underline{\mathbf{x}}$:

$$\mathbf{w} = \mathbf{E} \cdot \underline{\mathbf{x}} \tag{3.13}$$

In other words, the emissions are related to the sectoral throughput and, thus, they are endogenously determined, since $\mathbf{w}$ is a function of $\underline{\mathbf{x}}$.

$\mathbf{E}$ can be found by diagonalising both sides of the equation

$$\mathbf{E} = \hat{\mathbf{w}} \cdot \hat{\underline{\mathbf{x}}}^{-1} \tag{3.14}$$

The assumption that intermediate production is proportional to total outputs is maintained. However, since total output units include emissions, the technical coefficients matrix is

$$\underline{\mathbf{A}} = \mathbf{Z} \cdot \hat{\underline{\mathbf{x}}}^{-1} \tag{3.15}$$

By combining equations 3.13 and 3.15 into 3.2, Xu and Zhang derive a new Leontief inverse matrix which includes the emissions or, in other words, endogenises the emission generation in the production structure:

$$\underline{\mathbf{x}} = \underline{\mathbf{A}} \cdot \underline{\mathbf{x}} + \mathbf{f} + \mathbf{E} \cdot \underline{\mathbf{x}} \tag{3.16}$$

$$\underline{\mathbf{x}} = (\mathbf{I} - \underline{\mathbf{A}} - \mathbf{E})^{-1} \cdot \mathbf{f} \tag{3.17}$$

$$\underline{\mathbf{x}} = \underline{\mathbf{L}} \cdot \mathbf{f} \tag{3.18}$$

where

$$\underline{\mathbf{L}} = (\mathbf{I} - \underline{\mathbf{A}} - \mathbf{E})^{-1} \tag{3.19}$$

Xu and Zhang were therefore able to relate the final production $\mathbf{f}$ to $\underline{\mathbf{x}}$ by means of a modified Leontief inverse $\underline{\mathbf{L}}$ without requiring any unit change. The interpretation of $\underline{\mathbf{L}}$ is discussed in section 3.2.4.1.

Xu and Zhang method is in fact a new output-driven model, since it can only be applied to *multiple related final outputs* tables — IOTs with several final products whose production is related to each other — for which other IO models do not work. In other words, the Xu and Zhang model is capable of tracing by-products as final outputs, i.e. *outside* the intersectoral matrix[7].

In fact, IOTs with *multiple related final outputs* can be driven by any of the related final outputs because all final outputs are implicitly assumed to be linearly related to the total output. For example, if the generation of emissions — the related final output in the PIOT case — is linearly related to total output, so is the total production of goods (intermediate *plus* final) because what does not end up as emission ends up embedded in goods. This becomes clear by recalling the basic assumption of IOA whereby intermediate good production is linearly related to total outputs: since emissions and intermediate production are linearly related to total outputs and their sum together with final production equals total outputs (as seen in equation 3.2), final production is also linearly related to total outputs. The proof is provided by the Leontief inverse itself since it linearly relates final goods to total outputs. Thus, the model can be driven by either one of the components of final outputs (final goods or emissions) since both are linearly related to the total output.

Although it is more intuitive to apply the model with final goods because it is the production of final goods that drives the economic system, the model can also be driven

[7] Stone (1961) developed a method tracing the simultaneous production of primary and secondary goods *within* the intersectoral matrix (as explained in Nakamura and Kondo (2009, chap 3.2.2)), while Xu and Zhang's method traces the production of primary goods only *within* the intersectoral matrix and by-products (the disposal to nature) *outside* it, as a final output.

by emissions by making explicit the linear relation between final goods and total outputs:

$$\mathbf{f} = \mathbf{F} \cdot \underline{\mathbf{x}} \tag{3.20}$$

which used in equation 3.2 leads to

$$\underline{\mathbf{x}} = \underline{\mathbf{A}} \cdot \underline{\mathbf{x}} + \mathbf{F} \cdot \underline{\mathbf{x}} + \mathbf{w} \tag{3.21}$$

$$\underline{\mathbf{x}} = (\mathbf{I} - \underline{\mathbf{A}} - \mathbf{F})^{-1} \cdot \mathbf{w} \tag{3.22}$$

$$\underline{\mathbf{x}} = \underline{\mathbf{L}}^{var} \cdot \mathbf{w} \tag{3.23}$$

The column sum of $\underline{\mathbf{L}}^{var}$ can be interpreted as the total goods production (intermediate *and* final) required to produce one unit of emissions. This structure contains the same information than $\underline{\mathbf{L}}$, albeit organised in a different manner, therefore it is not further examined.

3.2.2.3 Dataset used for numerical applications and illustration

The dataset chosen for numerical applications and examples is the same used in Dietzenbacher et al. (2009), which is based on Nebbia (2000). The idea is to be able to compare the results of Xu and Zhang method to the results gathered in Dietzenbacher et al. (2009), where three different methods including Suh's method are tested. This dataset will also be used in the section 3.3, where PIOTs are represented as circular diagrams, and also in chapter 6, which illustrates how to apply the methods and indicators developed in chapters 4 and 5 to analyse the structure of a PIOT and identify how to improve its resource efficiency. By using the same dataset, it will become clearer that each method enables researchers to explore different structural aspects of the PIOT that could not be derived from examining the table on its own. Also, using an aggregated dataset containing three sector will make it easier for readers interested in reproducing manually the methodology to identify and extract the full cyclic structure developed in chapter 4.

The original PIOT developed by Nebbia (1999) contained the following sectors: the environment, agriculture, industry, household, waste treatment, stock, and import/exports. The PIOT was revised in a later publication (Nebbia, 2000) where the environment was further disaggregated between renewable resources embedded in air, water and soil, and non-renewable resources (e.g. fossil fuels); agriculture was disaggregated between agriculture and husbandry. In both cases, the PIOTs represent the material flows exchanged between the environment and the Italian economy in 1995 in million tons.

The dataset developed in Nebbia (2000) was aggregated by Dietzenbacher et al. (2009) as a three sectors PIOT with exogenous final demand, as presented in table 3.4. The agricultural sector aggregates the agricultural, forestry and feedstock activities which sell most its products to the manufacturing industry for further transformation. The manufacturing sector aggregates the extraction of abiotic resources and their transformation, the food processing sector, the manufacturing sector itself and the construction sector. The services sector comprises food services, accommodation, health care and transportation (Nebbia, 2000).

	Agric.	Manuf.	Serv.	Final demand	Waste	Total outputs
Agriculture	153	190	30	20	477	870
Manufacturing	66	845	74	658	667	2310
Services	33	29	10	67	97	236
Resources	618	1246	122			
Total inputs	870	2310	236			

TABLE 3.4: PIOT for Italy in 1995 in million tons (Dietzenbacher et al., 2009, table 7.2)

3.2.2.4 Numerical application

This section exemplifies the applications of both methods to the PIOT represented by table 3.4, first using Suh's method and second using Xu and Zhang's method.

Suh's method Applying the unit change with equation 3.5,

$$\mathbf{x} = \begin{pmatrix} 870 \\ 2310 \\ 236 \end{pmatrix} - \begin{pmatrix} 477 \\ 667 \\ 97 \end{pmatrix} = \begin{pmatrix} 393 \\ 1643 \\ 139 \end{pmatrix}$$

using equation 3.7,

$$\mathbf{A} = \begin{pmatrix} 0.389 & 0.116 & 0.216 \\ 0.168 & 0.514 & 0.532 \\ 0.084 & 0.018 & 0.072 \end{pmatrix}$$

Using equations 3.8 and 3.9

$$\mathbf{L} = \begin{pmatrix} 1.863 & 0.469 & 0.702 \\ 0.847 & 2.316 & 1.525 \\ 0.185 & 0.086 & 1.170 \end{pmatrix}$$

Total outputs due to producing one unit of agricultural final goods are

$$\mathbf{x} = \begin{pmatrix} 1.863 & 0.469 & 0.702 \\ 0.847 & 2.316 & 1.525 \\ 0.185 & 0.086 & 1.170 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1.863 \\ 0.847 \\ 0.185 \end{pmatrix}$$

Using equation 3.11, the corresponding waste generated is

$$\mathbf{w} = \hat{\mathbf{c}}^{w} \cdot \mathbf{x} = \begin{pmatrix} 1.214 & 0 & 0 \\ 0 & 0.406 & 0 \\ 0 & 0 & 0.698 \end{pmatrix} \cdot \begin{pmatrix} 1.863 \\ 0.847 \\ 0.185 \end{pmatrix} = \begin{pmatrix} 2.261 \\ 0.344 \\ 0.129 \end{pmatrix}$$

Therefore, to produce one unit of agricultural final product, sector 1 produces 2.261 units of emissions, sector 2 produces 0.344 units of emissions, and sector 3 produces 0.129 units of emissions.

Xu and Zhang's method Using equation 3.15,

$$\underline{\mathbf{A}} = \begin{pmatrix} 0.176 & 0.082 & 0.127 \\ 0.076 & 0.366 & 0.314 \\ 0.038 & 0.013 & 0.042 \end{pmatrix} \tag{3.24}$$

Note that all technical coefficients of $\underline{\mathbf{A}}$ differ from $\mathbf{A}$, implying a different production structure. Then, using equation 3.13,

$$\mathbf{E} = \begin{pmatrix} 477 & 0 & 0 \\ 0 & 667 & 0 \\ 0 & 0 & 97 \end{pmatrix} \cdot \begin{pmatrix} 0.0011 & 0 & 0 \\ 0 & 0.0004 & 0 \\ 0 & 0 & 0.0042 \end{pmatrix} = \begin{pmatrix} 0.548 & 0 & 0 \\ 0 & 0.289 & 0 \\ 0 & 0 & 0.411 \end{pmatrix} \tag{3.25}$$

Following equation 3.19,

$$\underline{\mathbf{L}} = \begin{pmatrix} 4.124 & 1.039 & 1.555 \\ 1.190 & 3.256 & 2.145 \\ 0.314 & 0.147 & 1.987 \end{pmatrix} \tag{3.26}$$

Note that all coefficients of $\underline{\mathbf{L}}$ also differ from $\mathbf{L}$, implying that structural analyses based on the Leontief inverse will provide different results; this analytical divergence between the two methods is analysed in section 3.2.4.1.

Equation 3.18 is then used to find the total outputs associated with one unit of final demand from the agricultural sector

$$\underline{\mathbf{x}} = \begin{pmatrix} 4.124 & 1.039 & 1.555 \\ 1.190 & 3.256 & 2.145 \\ 0.314 & 0.147 & 1.987 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 4.124 \\ 1.190 \\ 0.314 \end{pmatrix} \tag{3.27}$$

And finally, using equation 3.13,

$$\mathbf{w} = \begin{pmatrix} 0.548 & 0 & 0 \\ 0 & 0.289 & 0 \\ 0 & 0 & 0.411 \end{pmatrix} \cdot \begin{pmatrix} 4.124 \\ 1.190 \\ 0.314 \end{pmatrix} = \begin{pmatrix} 2.261 \\ 0.344 \\ 0.129 \end{pmatrix} \tag{3.28}$$

which are the same emission values found with Suh's method.

Thus, Suh's method (Suh, 2004b) is *operationally* equivalent to Xu and Zhang's (Xu and Zhang, 2009), as demonstrated in the appendix of the latter; both methods allow the calculation of the emissions and primary resources related to any given final demand.

3.2.3 Indirect structural analysis

By examining the primary resource requirements or the emissions associated with a given final demand, the researcher is in fact indirectly exploring the structure of the economy. In particular, when calculated per unit of final demand, emissions indicate the emission intensity of the economy associated with the production of a given final good, revealing the relative weight that each final product has in the total emissions of the economy. Therefore, the intensities indirectly explain the composition of total emissions — i.e. the current metabolism of the economy. This section shows that such indirect analyses can hint at structural features (e.g. sectoral or system-wide resource efficiencies) that can be further explored by a (direct) structural analysis (i.e. an analysis of the **A** or **L** matrix).

The emissions associated with the production of a unit of final goods of the agricultural, manufacturing and services sector from the PIOT used in the previous example (table 3.4) are, respectively,

$$\mathbf{w}^{agr.} = \begin{pmatrix} 2.261 \\ 0.344 \\ 0.129 \end{pmatrix}, \mathbf{w}^{man.} = \begin{pmatrix} 0.569 \\ 0.940 \\ 0.060 \end{pmatrix}, \mathbf{w}^{ser.} = \begin{pmatrix} 0.853 \\ 0.619 \\ 0.817 \end{pmatrix} \tag{3.29}$$

and, due to the linear relationships, the total amount of emissions equals the emission intensity of each final good times the amount of final goods produced in total,

$$\mathbf{w} = 20 \cdot \mathbf{w}^{agr.} + 658 \cdot \mathbf{w}^{man.} + 67 \cdot \mathbf{w}^{ser.} \tag{3.30}$$

By analysing emission intensities, several structural attributes of the economy can be noted indirectly: for example, that the services sector induces more agricultural emissions (0.853) than the manufacturing sector (0.569) per unit of final goods produced; or that the agricultural sector produces the most total emissions[8] per unit of final goods (2.734) compared to the services (2.288) and manufacturing (1.570) sectors. These last three results can be reinterpreted as follows: the economy is more resource efficient when producing one final unit of a manufactured good than when producing a final unit of a service or agricultural good; agricultural goods being the least resource efficient. In other words, the agricultural sector is the one relatively driving most emissions and primary resource consumption.

This results might seem counter-intuitive for readers used to *relative indicators*, in which material flows are related to their contribution to the GDP (UNEP, 2011a). Usually, the services sector performs the best in relative terms, not because it uses less resources but because it generates more added value per unit of materials used. However, in absolute terms, i.e. using *absolute indicators* looking at the physical impact only, the relationship between sectors changes, as demonstrated in the example above.

Evaluating equation 3.30 reveals which final goods drive most emissions in absolute terms:

$$\begin{pmatrix} 477 \\ 667 \\ 97 \end{pmatrix} = \begin{pmatrix} 45 \\ 7 \\ 3 \end{pmatrix} + \begin{pmatrix} 375 \\ 619 \\ 40 \end{pmatrix} + \begin{pmatrix} 57 \\ 41 \\ 55 \end{pmatrix} \tag{3.31}$$

Here, it is manufacturing activity which induces the most total agricultural emissions (375), despite being the least emission intense in relative terms (0.569).

However, the structural reason for the different emission intensities (and thus behind the relative contribution of each final product in generating those emissions) requires direct analysis of the physical structure of the economy. In other words, indirect analyses alone cannot reveal why the economy produces specific amounts of emissions but highlights trends that can be subsequently explored by direct structural analyses, such as the backward linkage analysis performed in section 3.2.4.2.

[8] Defined as the norm of the emission vectors ($\mathbf{w}^{agr.}$, $\mathbf{w}^{man.}$ and $\mathbf{w}^{ser.}$) generated per unit of final goods.

Similar indirect analysis can be performed using the resource intensities, i.e., calculating the amount of resources required to produce one unit of final demand by using input coefficients for the primary resource row, as defined in equation 3.11.

3.2.4 Direct structural analysis

In section 3.2.2, Suh's and Xu and Zhang methods (Suh, 2004b; Xu and Zhang, 2009) were reviewed, observing their operational equivalence — i.e. they find the same primary inputs and final emissions due to a given final demand. However, it was noted that the productive structures represented by their corresponding technical coefficients and Leontief inverse matrices are different. Thus, the questions arising are: are the physical structures revealed by both methods equivalent? If not, which one should be used for structural analyses?

3.2.4.1 Analytical interpretation of the structures derived from Suh (2004) and Xu and Zhang (2009) methods

Recalling section 3.2.2.1, Suh's method (Suh, 2004b) literally subtracts the emissions from the original PIOT. The new PIOT reveals the flow of primary resources that are embedded in final goods only — i.e. it represents a structure tracing a fraction of the total primary resources used by the economy: the fraction embedded in final goods, not a structure tracing all primary resources required for production. So, Suh's method removes the information that PIOTs provide in terms of tracing emissions and, thus, this physical structure is closer to the corresponding MIOT since MIOTs do not represent emissions either. Thus, the physical structure derived from Suh's method and the monetary structure represented by its corresponding MIOT are similar because, although the PIOTs include emission flows that are excluded in MIOT, Suh's method subtracts them from the PIOT, which is transformed into a structure representing the material flows that are only embedded in final goods (c.f. table 3.3). Only in this case, the statement of Weisz and Duchin (2006) that MIOTs and PIOTs' structures are *similar* holds.

From now on, the structures revealed by Suh's method (**A** and **L**) are called the *goods-only structure* since they represent the total requirements of the economy to produce final products in "goods units" (i.e. in tons of goods). **A** and **L** represent the physical structure of the economy exclusively related to goods, because the flows related to emissions are removed from the technical coefficients matrix by the change of units. Therefore, these structures do not represent *all* physical flows required to produce those goods — i.e. the flows embedded in final products *and* lost as disposals to nature — but only the structure of the materials that are embedded in products.

Conversely, the Xu and Zhang model (Xu and Zhang, 2009) finds different structures, $\underline{\mathbf{A}}$ and $\underline{\mathbf{L}}$, representing the production structure taking into account the flows related to disposals to nature. They represent the total requirements of the economy to produce goods and emissions in "goods *and* emission units" (i.e. in tons of goods and emissions). Therefore, they represent the "real" physical structure of the economy: including all material required for production, even the primary resources "lost" as emissions. From now on, this structure will be referred to as the *complete physical structure* since it includes *all* materials required to produce goods. Thus, the *goods-only physical structure* is a partial representation of the *complete physical structure* since it only represents the primary resources embedded in goods.

Since the *goods-only* and *complete* structures represent different flow structures, they are different — as seen in the previous numerical examples in sections 3.2.2.4 and 3.2.2.4 —, and their corresponding structural analyses will consequently gather different results.

Starting by subtracting $\mathbf{Z} \cdot \mathbf{i}$ on both sides of equation 3.5,

$$\mathbf{x} - \mathbf{Z} \cdot \mathbf{i} = \underline{\mathbf{x}} - \mathbf{Z} \cdot \mathbf{i} - \mathbf{w} \tag{3.32}$$

$$\mathbf{x} - \mathbf{A} \cdot \mathbf{x} = \underline{\mathbf{x}} - \underline{\mathbf{A}} \cdot \underline{\mathbf{x}} - \mathbf{E} \cdot \underline{\mathbf{x}} \tag{3.33}$$

$$\mathbf{L} \cdot \mathbf{x} = \underline{\mathbf{L}} \cdot \underline{\mathbf{x}} \tag{3.34}$$

$$\mathbf{L} = \underline{\mathbf{L}} \cdot \hat{\underline{\mathbf{x}}} \cdot \hat{\mathbf{x}}^{-1} \tag{3.35}$$

Since equation 3.35 is not of the form $A = G \cdot B \cdot H$, relating two invertible matrices G and H with the two linear transformations A and B, $\mathbf{L}$ and $\underline{\mathbf{L}}$ are non-equivalent and, consequently, non-similar; thus, they do not necessarily share any properties[9].

So, equation 3.35 constitutes the algebraic demonstration that the Leontief inverse matrices revealed by the Suh and Xu and Zhang methods (Suh, 2004b; Xu and Zhang, 2009) are completely different, and the difference stems from the change of units (not base) that Suh applies on the PIOT to transform it from a two final outputs IOT into a single final output IOT (see equation 3.5).

As expected, the same relationship is observed between $\mathbf{A}$ and $\underline{\mathbf{A}}$: using equations 3.7 and 3.15,

$$\mathbf{A} \cdot \mathbf{x} = \underline{\mathbf{A}} \cdot \underline{\mathbf{x}} \tag{3.36}$$

$$\mathbf{A} = \underline{\mathbf{A}} \cdot \hat{\underline{\mathbf{x}}} \cdot \hat{\mathbf{x}}^{-1} \tag{3.37}$$

[9] Similar matrices are a special case of equivalent matrices (so non-equivalent matrices cannot be similar) and only similar matrices share the same properties, e.g., rank, characteristic polynomial, etc. (Ames, 1970). An example in IOA is the similarity between the Leontief and Ghosh inverse matrices (Miller and Blair, 2009, chap. 12.1.2).

These results are key because they mean that the two physical structures revealed by the two methods are different and, thus, it is unclear which one should be used to analyse the physical structure of the economic system.

3.2.4.2 Backward linkage analysis of the *goods-only* and *complete* physical structures

To illustrate and interpret the structural difference between the *goods-only* and *complete* structures, a backward linkage analysis is performed on both structures.

Direct backward linkages are based on the technical coefficients matrix; total backward linkages — which entail the direct and indirect sectoral relationships — are based on the Leontief inverse matrix (Miller and Blair, 2009, chap. 12).

The measures of direct backward linkage for each sector are given by

$$\mathbf{b}^{direct} = \mathbf{i}' \cdot \mathbf{A} \tag{3.38}$$

Since direct backward linkages represent the proportion of domestic requirements used to produce one unit of sectoral output, they can be interpreted as a dependence percentage on the intermediate production of the sector to produce its final product. Thus, $\mathbf{i}' - \mathbf{b}^{direct}$ represent the dependence percentage on primary inputs (primary resources in the PIOT case).

The direct measures can be normalised so as to compare them to the mean of the economy. A typical normalised form of the backward linkage measures for an n sectors intersectoral matrix is

$$\bar{\mathbf{b}}^{direct} = \frac{n \cdot \mathbf{i}' \cdot \mathbf{A}}{\mathbf{i}' \cdot \mathbf{A} \cdot \mathbf{i}} \tag{3.39}$$

Total backward linkage measures for each sector are given by

$$\mathbf{b}^{total} = \mathbf{i}' \cdot \mathbf{L} \tag{3.40}$$

Total backward linkages represent total (direct and indirect) domestic activity to produce one unit of final output; thus, each measure can be interpreted as the total amount of materials circulated and transformed within the economy to produce one unit of each sector's final good. Since the *goods-only physical structure* represents exclusively the materials embedded in intermediate and final goods (not transformed into emissions), its total measures represent the total amount of materials circulated and transformed into goods only. However, the *complete physical structure* additionally entails the emissions generated during the production of the intermediate and final goods, so its total measures represent the total amount of materials circulated and transformed into goods *and* emissions. Thus, the fraction of the total backward linkages corresponding to emissions (i.e. the emissions generated by each sector to produce one unit of their corresponding final demand) can also[10] be calculated as $\mathbf{b}^{total\ (complete\ structure)} - \mathbf{b}^{total\ (goods-only\ structure)}$.

The normalised measures of the total backward linkages are

$$\bar{\mathbf{b}}^{total} = \frac{n \cdot \mathbf{i}' \cdot \mathbf{L}}{\mathbf{i}' \cdot \mathbf{L} \cdot \mathbf{i}} \tag{3.41}$$

Table 3.5 shows the direct backward linkages for the *complete* and *goods-only* structures of the PIOT used in the previous examples (table 3.4); the total backward linkages are reported in table 3.6. Additionally, table 3.7 shows the proportion of inputs used from intermediate production (i.e. the absolute direct backward linkages represented as percentage) and the inputs used from primary resources (the rest of the percentage over 100%); table 3.8 disaggregates total domestic activity (i.e. absolute total backward linkages) by the type of product: either good or emission, as explained at the end of the previous paragraph.

	Goods-only physical structure			Complete physical structure		
	Agricul.	Manufac.	Serv.	Agricul.	Manufac.	Serv.
$\mathbf{b}^{direct}$	0.64	0.65	0.82	0.29	0.46	0.48
$\bar{\mathbf{b}}^{direct}$	0.91	0.92	1.17	0.70	1.12	1.18

TABLE 3.5: Absolute and normalised direct backward linkage measures of the goods-only and complete physical structures.

	Goods-only physical structure			Complete physical structure		
	Agricul.	Manufac.	Serv.	Agricul.	Manufac.	Serv.
$\mathbf{b}^{total}$	2.89	2.87	3.40	5.63	4.44	5.69
$\bar{\mathbf{b}}^{total}$	0.95	0.94	1.11	1.07	0.85	1.08

TABLE 3.6: Absolute and normalised total backward linkage measures of the goods-only and complete physical structures.

3.2.4.3 Discussion

A structure is characterised by both its absolute and normalised values; the former revealing an order between the different elements of the structure, the latter representing their relative importance. The structure determined by three sectors A, B and C,

[10] The total emissions generated to produce one unit of final goods can be calculated as in section 3.2.2.4.

	Goods-only physical structure			Complete physical structure		
	Agricul.	Manufac.	Serv.	Agricul.	Manufac.	Serv.
$\mathbf{b}^{direct}$	0.64	0.65	0.82	0.29	0.46	0.48
Dependence on:						
intermed. prod.	64%	65%	82%	29%	46%	48%
primary res.	36%	35%	18%	71%	54%	52%

TABLE 3.7: Relationship between absolute direct backward linkages of the goods-only and complete physical structures and their dependence on intermediate production and primary resources.

	Goods-only physical structure			Complete physical structure		
	Agricul.	Manufac.	Serv.	Agricul.	Manufac.	Serv.
$\mathbf{b}^{total}$	2.89	2.87	3.40	5.63	4.44	5.69
Circulation and transformation of materials as:						
goods	2.89	2.87	3.40	2.89	2.87	3.40
emissions	0	0	0	2.74	1.57	2.29

TABLE 3.8: Relationship between absolute total backward linkages of the goods-only and complete physical structures and their composition by type of product (either goods or emissions).

respectively requiring 64%, 65% and 82% of their inputs from intermediate resources, is not the same as three sectors ABC requiring 29%, 46%, and 48% of their inputs from intermediate resources. In both cases, the absolute values suggest the same order (ABC) but the relative importance of the sectors is different, revealing a different structure: in the first case, A and B are below average and only C is above average, so C requires much more intermediate resources than the other sectors; in the second case, only A is below average and B and C are above average, so in this structure both B and C require more intermediate resources than the average of the economy. In fact, these numbers are the results derived from the direct backward analysis for the case of both goods-only and complete structures (c.f. table 3.5). Thus, even if the absolute order is maintained in both structures[11], their relative importance differs, as revealed by the change in the normalised values in table 3.5 (a value of 1 stands for the average of the economy).

In this case, the absolute direct backward linkages of the *goods-only* physical structure are higher than their *complete* physical structure counterpart because the *goods-only* structure does not include the "extra" primary resources that are disposed to nature. Thus, in the *goods-only* structure, each sector has lower direct dependence on primary resources (i.e. higher backward dependence on intersectoral inputs), increasing the proportion of the

[11] The order is not always necessarily maintained.

intersectoral inputs with respect to total inputs, leading to higher dependence on direct backward linkages compared to the *complete* structure (c.f. table 3.7).

Coincidentally, the ranking of absolute total measures is the same in both structures; however, their relative structure is also altered, as revealed by the normalised measures in table 3.6: while only the services sector is above average in the *goods-only* structure (1.11), both the services and the agricultural sectors are above average in the *complete* structure (1.07 and 1.08 respectively). In other words, while the agricultural sector might seem to induce total domestic activity below average when analysing *the goods-only* structure (0.95), it is in fact above average as revealed by the *complete* structure (1.07).

To explain the different total values in both structures, the key is to focus on the flows that are not represented in the *goods-only* structure: emissions, i.e. resources not embedded in goods. Table 3.8 represents the total domestic activity associated with the *goods-only* and *complete* structures, disaggregated by goods or emissions. The agricultural sector generates the most emissions per unit of final good produced (2.74 against 1.57 and 2.29, table 3.8); thus, the relative structure will be altered when including the emissions: the agricultural sector will experience a relative increase in the total domestic activity from below average (0.95) in the goods-only structure to above average (1.07) in the complete structure (c.f. table 3.6).

The results confirm that the two methods represent totally different structures: the Suh method reveals the *goods-only physical structure* that only considers the resources that are embedded in goods (therefore excluding the resources that are embedded in the emissions) while the Xu and Zhang model reveals the *complete physical structure* of the economy considering all materials required for production, including the ones lost as emissions.

However, when aiming to analyse the *complete* structure of the economy — i.e. including *all* materials flows related to production, not the material flows related exclusively to goods —, only the Xu and Zhang method is appropriate; in this case, the Suh method can only provide complementary information to help interpret the results, as has been illustrated in this section. Thus, since the aim of this thesis is to analyse the *complete* physical structure of the economy, only the Xu and Zhang method will be used in chapter 4 to develop further methods for structural analysis.

Furthermore, the results here discussed provide additional insights into the results found in the indirect analysis of section 3.2.3. For example, the disaggregation of the absolute total backward linkages provided in table 3.8 reveals that, in the agricultural sector, the proportion between emissions and units of goods produced is the highest (2.74 compared to 1.57 and 2.29), despite other sectors inducing similar or even more domestic activity (2.89 compared to 2.87 and 3.40), i.e. more transformation of intermediate goods. In other words, the economic system is more resource efficient when producing manufacturing and service final goods not only because it generates less total emissions per unit of final good but also because it induces more domestic activity related to goods, i.e. generates less emissions per unit of intermediate goods transformed. Also, using the information of the direct measures (i.e. high reliance on primary resources of the agricultural sector (71%, table 3.7)), it can be ascertained that most emissions generated by the agricultural sector stem from agricultural primary resources $\mathbf{r}_1$, hence the agricultural component of $\mathbf{w}_1^{agr.}$ can be predicted to be markedly higher than the others, as is the case (2.261 >> 0.344 and 0.129).

3.2.5 Analysing PIOTs tracing several emissions simultaneously

Next, both methods are generalised to build and analyse PIOTs representing several emissions simultaneously. Emissions is a general term to represent different waste types such as solid wastes or wastes for incineration, different emissions types such as carbon dioxide or sulphur, or different emission pathways such air- or water-borne emissions, depending on the disaggregation level required for the analysis. The production structure can then be analysed as described in the previous sections.

Tracing several emissions simultaneously makes it possible to reveal relationships that were previously "hidden" due to the aggregation of emissions. In particular, PIOTs tracing several emissions allow analysis of relationships between specific resources and specific emissions, and also between different emissions themselves. This section has been included for completeness with the aim to provide more analytical applications for the PIOT framework. This is especially relevant since economic activities generate more than one emission type, so IO models need to be able to cope with PIOTs representing several emission types if PIOTs are to be used for real case studies. However, due to the limited scope of this thesis, analyses using these generalised methods are not provided, but their use will be discussed in the conclusion chapter.

3.2.5.1 Generalising Xu and Zhang (2009)'s method

Theory Xu and Zhang's model is now generalised for an IOT with m *multiple related final outputs* by endogenising $m-1$ of the related final outputs within the Leontief inverse; the final output that is not endogenised is the one driving the model.

In a PIOTs with m *multiple related final outputs*, final demand $\mathbf{f}$ is chosen to drive the model and the other $m-1$ multiple related outputs — the different emissions of the

PIOT represented as $\mathbf{w}_k$ with $k = [1, ..., m-1]$ — are endogenised in the production structure. Equation 3.16 is modified to accommodate the $m-1$ emissions:

$$\underline{\mathbf{x}} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} + \mathbf{w}_1 + \mathbf{w}_2 + \ldots + \mathbf{w}_{m-1} \tag{3.42}$$

The technical coefficients matrix is calculated as in the single emission case (using equation 3.15); and equation 3.13 is used for each disposal to endogenise them all in the production structure:

$$\underline{\mathbf{x}} = \mathbf{A} \cdot \underline{\mathbf{x}} + \mathbf{f} + \mathbf{E}_1 \cdot \underline{\mathbf{x}} + \mathbf{E}_2 \cdot \underline{\mathbf{x}} + \ldots + \mathbf{E}_{m-1} \cdot \underline{\mathbf{x}} \tag{3.43}$$

$$\underline{\mathbf{x}} = (\mathbf{I} - \mathbf{A} - \mathbf{E}_1 - \mathbf{E}_2 - \ldots - \mathbf{E}_{m-1})^{-1} \cdot \mathbf{f} = \underline{\mathbf{L}} \cdot \mathbf{f} \tag{3.44}$$

The Leontief inverse resembles the one in equation 3.19 but now includes $m-1$ emissions:

$$\underline{\mathbf{L}} = (\mathbf{I} - \mathbf{A} - \mathbf{E}_1 - \mathbf{E}_2 - \ldots - \mathbf{E}_{m-1})^{-1} \tag{3.45}$$

Despite endogenising $m-1$ emissions in the production structure, the interpretation of the Leontief inverse remains the same: the column sum of $\underline{\mathbf{L}}$ represents the total physical activity of the economy (i.e. the intermediate goods and emissions) required to produce one unit of final demand.

After calculating the total amount of materials $\underline{\mathbf{x}}$ mobilised due to a specific final demand $\mathbf{f}$, the corresponding generation of each emission $\mathbf{w}_k$ can be calculated using equation 3.18 with the corresponding waste generation matrix $\mathbf{E}_k$:

$$\mathbf{w}_k = \mathbf{E}_k \cdot \underline{\mathbf{x}} \tag{3.46}$$

Numerical example The single emission column from table 3.4 is hypothetically disaggregated into five different emission and waste types represented in table 3.9.

	Agri.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}_1$	$\mathbf{w}_2$	$\mathbf{w}_3$	$\mathbf{w}_4$	$\mathbf{w}_5$	$\underline{\mathbf{x}}$
Agriculture	153	190	30	20	100	55	50	125	147	870
Manufacturing	66	845	74	658	230	45	185	145	62	2310
Services	33	29	10	67	45	10	15	25	2	236
Resources $\mathbf{r}'$	618	1246	122							
Total inputs $\underline{\mathbf{x}}'$	870	2310	236							

TABLE 3.9: IOT with six multiple related outputs: final goods, two waste types and three emission types: solid waste $\mathbf{w}_1$, waste for incineration $\mathbf{w}_2$, emissions to air $\mathbf{w}_3$, emissions to water $\mathbf{w}_4$, and emissions to soil $\mathbf{w}_5$

Next, the amount of each type of emission generated to produce one unit of final goods by the services sector is calculated. The technical coefficients matrix is the same as in the previous example. The output coefficient matrices for each emission are: $\mathbf{E}_1 = \begin{pmatrix} 0.115 & 0 & 0 \\ 0 & 0.100 & 0 \\ 0 & 0 & 0.191 \end{pmatrix}$, $\mathbf{E}_2 = \begin{pmatrix} 0.063 & 0 & 0 \\ 0 & 0.019 & 0 \\ 0 & 0 & 0.042 \end{pmatrix}$, $\mathbf{E}_3 = \begin{pmatrix} 0.057 & 0 & 0 \\ 0 & 0.080 & 0 \\ 0 & 0 & 0.064 \end{pmatrix}$, $\mathbf{E}_4 = \begin{pmatrix} 0.144 & 0 & 0 \\ 0 & 0.063 & 0 \\ 0 & 0 & 0.106 \end{pmatrix}$ and $\mathbf{E}_5 = \begin{pmatrix} 0.169 & 0 & 0 \\ 0 & 0.027 & 0 \\ 0 & 0 & 0.008 \end{pmatrix}$.

Thus,

$$\underline{\mathbf{L}} = (\mathbf{I} - \underline{\mathbf{A}} - \mathbf{E}_1 - \mathbf{E}_2 - \mathbf{E}_3 - \mathbf{E}_4 - \mathbf{E}_5)^{-1} = \begin{pmatrix} 4.124 & 1.039 & 1.555 \\ 1.190 & 3.256 & 2.145 \\ 0.314 & 0.147 & 1.987 \end{pmatrix} \tag{3.47}$$

So, the total throughput of each sector of the economy $\underline{\mathbf{x}}$ for the services sector to produce one unit of final goods is

$$\underline{\mathbf{x}} = \begin{pmatrix} 4.124 & 1.039 & 1.555 \\ 1.190 & 3.256 & 2.145 \\ 0.314 & 0.147 & 1.987 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1.55 \\ 2.14 \\ 1.99 \end{pmatrix} \tag{3.48}$$

Finally, using equation 3.46, the corresponding emissions are: $\mathbf{w}_1 = \begin{pmatrix} 0.18 \\ 0.21 \\ 0.38 \end{pmatrix}$, $\mathbf{w}_2 = \begin{pmatrix} 0.10 \\ 0.04 \\ 0.08 \end{pmatrix}$, $\mathbf{w}_3 = \begin{pmatrix} 0.09 \\ 0.17 \\ 0.13 \end{pmatrix}$, $\mathbf{w}_4 = \begin{pmatrix} 0.22 \\ 0.13 \\ 0.21 \end{pmatrix}$ and $\mathbf{w}_5 = \begin{pmatrix} 0.26 \\ 0.06 \\ 0.02 \end{pmatrix}$. For each unit of final goods produced by the services sector, the agricultural sector produces 0.18 units of solid waste ($\mathbf{w}_1$), 0.10 units of incineration waste ($\mathbf{w}_2$), 0.09 units of air emissions ($\mathbf{w}_3$), 0.22 units of water emissions ($\mathbf{w}_4$) and 0.26 units of soil emissions ($\mathbf{w}_5$), and so on for the emissions of the manufacturing and services sectors.

3.2.5.2 Generalising Suh (2004) method

Theory The unit change must be generalised to accommodate the new emissions, so equation 3.5 becomes

$$\underline{\mathbf{x}} = \mathbf{x} + \mathbf{w_1} + \ldots + \mathbf{w_{m-1}} \tag{3.49}$$

Thus, all $m-1$ emissions are to be subtracted from the PIOT, each becoming a negative primary input row. The unit of the total output of the PIOT remains "tons of goods" and both the technical coefficients matrix and the Leontief inverse can be calculated as for the single emission case, since this change of units leaves the PIOT with a single final output (c.f. equations 3.7 and 3.10).

To calculate emissions corresponding to a given final demand, the emission "input" coefficients corresponding to each of the $m-1$ emissions need to be calculated by generalising equation 3.11 as

$$\mathbf{c}^{w_k} = \mathbf{w_k}' \cdot \hat{\mathbf{x}}^{-1} \tag{3.50}$$

Numerical example Using equation 3.49, table 3.9 becomes table 3.10.

	Agriculture	Manufacturing	Services	$\mathbf{f}$	$\mathbf{x}$
Agriculture	153	190	30	20	393
Manufacturing	66	845	74	658	1643
Services	33	29	10	67	139
Resources	618	1246	122		
$-\mathbf{w}'_1$	-100	-230	-45		
$-\mathbf{w}'_2$	-55	-45	-10		
$-\mathbf{w}'_3$	-50	-185	-15		
$-\mathbf{w}'_4$	-125	-145	-25		
$-\mathbf{w}'_5$	-147	-62	-2		
$\mathbf{x}'$	393	1643	139		

TABLE 3.10: PIOT with six related outputs transformed into a single output table by changing the total output units from $\underline{\mathbf{x}}$ to $\mathbf{x}$.

The technical coefficients matrix and Leontief inverse are the same as calculated for the single emission case, as seen in section 3.2.2.1. Only the emission "input" coefficients need to be calculated following equation 3.50: $\mathbf{c}^{w_1} = \begin{pmatrix} 0.25 & 0.14 & 0.32 \end{pmatrix}$, $\mathbf{c}^{w_2} = \begin{pmatrix} 0.14 & 0.03 & 0.07 \end{pmatrix}$, $\mathbf{c}^{w_3} = \begin{pmatrix} 0.13 & 0.11 & 0.11 \end{pmatrix}$, $\mathbf{c}^{w_4} = \begin{pmatrix} 0.13 & 0.11 & 0.11 \end{pmatrix}$ and $\mathbf{c}^{w_5} = \begin{pmatrix} 0.37 & 0.04 & 0.01 \end{pmatrix}$.

Using those emission coefficients, the emissions generated to produce one unit of final goods in the service sector can be calculated and will match the ones found in section 3.2.5.1.

3.2.5.3 Building PIOTs with several disposals to nature

PIOTs that include several emissions can be directly built as such by compiling information on the emissions derived from the extraction and transformation of a specific material at the required disaggregation level. However, PIOTs are usually built for single materials or material categories (Pedersen, 1998). In this case, it is interesting to aggregate them to assess how different materials are exchanged. Nevertheless, it is also interesting to maintain the emissions disaggregated since different type of emissions can cause different environmental impacts. This section illustrates how to aggregate several PIOTs tracing a single material flow into a single PIOT with different emission types (which correspond to the single emissions of each original PIOT).

Consider three PIOTs with a single emission each, with its components ($\mathbf{r}$, $\mathbf{Z}$, $\mathbf{f}$, $\mathbf{w}$ and $\underline{\mathbf{x}}$) identified with the corresponding super-indices 1, 2 and 3. The resulting aggregated PIOT would entail a single intersectoral matrix $\mathbf{Z}$ and a single final demand $\mathbf{f}$ but three separate resource rows and emission columns, as shown in table 3.11. PIOTs originally tracing several emissions can also be aggregated in this manner.

	Sector 1 ... Sector n	$\mathbf{f}$	Emissions			$\underline{\mathbf{x}}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^1 + \mathbf{Z}^2 + \mathbf{Z}^3$	$\mathbf{f}^1 + \mathbf{f}^2 + \mathbf{f}^3$	$\mathbf{w}^1$	$\mathbf{w}^2$	$\mathbf{w}^3$	$\underline{\mathbf{x}}^1 + \underline{\mathbf{x}}^2 + \underline{\mathbf{x}}^3$
Resources	$\mathbf{r}^{1\prime}$ $\mathbf{r}^{2\prime}$ $\mathbf{r}^{3\prime}$					
$\underline{\mathbf{x}}'$	$\underline{\mathbf{x}}^{1\prime} + \underline{\mathbf{x}}^{2\prime} + \underline{\mathbf{x}}^{3\prime}$					

TABLE 3.11: Three single emission PIOTs aggregated in a single PIOT maintaining the emissions and resources disaggregated.

3.3 Using circular diagrams

IOA has developed several analytical tools, such as structural decomposition analysis or linkage analysis (Miller and Blair, 2009). However, capturing and understanding structural features and patterns still remains a challenge given the large amount of data that IOTs contain. This is especially true when aiming to identify patterns at disaggregated level, i.e. related to the flows and not to the aggregation of flows. In this case, previous IOA methods for structural analysis cannot contribute to this end, since they are based on aggregate indicators. For instance, the backward linkage analysis compares the values of the technical coefficients and Leontief matrices aggregated by sector (c.f. section 3.2.4.2), but the same linkage measures might mask different intersectoral structures or, alternatively, different linkage measures might mask similar intersectoral structures.

So, this section explores how to perform structural analyses in a more disaggregated fashion, trying to identify structural patterns which are usually masked with conventional analyses such as linkage analysis. In particular, a visual analysis tool is developed, which makes it possible to recognise structural patterns and perform structural analyses at a disaggregated level.

3.3.1 Current and ideal visualisation of a system with internal and external flows for disaggregated structural analysis

This section illustrates the caveats of current visualisation tools to identify structural patterns. It also identifies the ideal features of a visualisation methodology enabling researchers to perform disaggregated structural analyses.

The economic system entails flow exchanges between its sectors, called *internal* flows to convey its location regarding the system's boundary. It also entails *external* flows, which represent the flows entering or leaving the system.

IOTs represent both the *internal* and *external* flows in a compact manner. Each value of the intersectoral matrix represents the internal (intersectoral) exchanges between every two sectors, i.e. the *internal* input and output flows of a sector. Also, IOTs contain information on the *external* input and output flows, i.e. how much each sector extracts and restores to the external system. In the case of a PIOT, the external inflows correspond to resources extracted or imported, and the external outflows correspond to the final goods and emissions produced.

As seen in the literature review (c.f. section 2.4.5), IOTs can be visually represented by either 2D or 3D colour coded matrices (Kondo et al., 2011; Sonis et al., 2000). However, colour coding cell values might mask underlying structural patterns, either because the colour scale is too aggregated, or on the other extreme, because the eye is not sensitive enough to associate values to a colour scale based on a continuous colour gradient. Figure 3.1 represents the PIOT from table 3.4 as a colour coded 2D matrix. In this case, since most intersectoral values are below 200, intersectoral patterns are masked. Additionally, the contribution of each flow to the total sectoral throughput cannot be established because even if the total throughput was drawn in an extra colour coded cell, it is difficult to identify the proportional contribution of each cell based on a colour pattern.

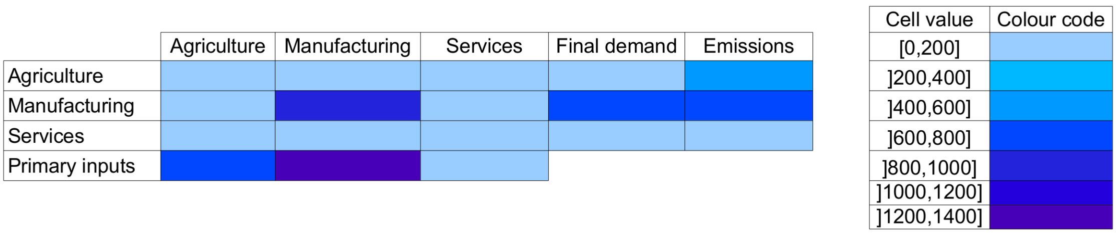

FIGURE 3.1: 2D colour coded matrix representing the PIOT from table 3.4 (in million tons)

Flowcharts and Sankey diagrams usually represent each sector explicitly (usually by a box) and represent the *internal* and *external* flows by arrows. Sectors are positioned to avoid crossing the arrows although the box position might also have a "meaning": e.g. bottom boxes are the source of external inflows, sectors are placed in the middle of the diagram and right hand boxes are external outflows. The size of the arrows can be proportional to the value of the flow. This is the characteristic feature of Sankey diagrams (Schmidt, 2008a) but can also be used in conventional flowcharts (Baccini and Brunner, 1991; Brunner et al., 1998). This enables the researcher to perform a visual assessment of the flows values. Figure 3.2 represents the PIOT from table 3.4 as a flowchart where the flows' size is proportional to their value. It has been drawn with STAN, a freeware software developed for Material Flow Analysis (Cencic and Rechberger, 2008).

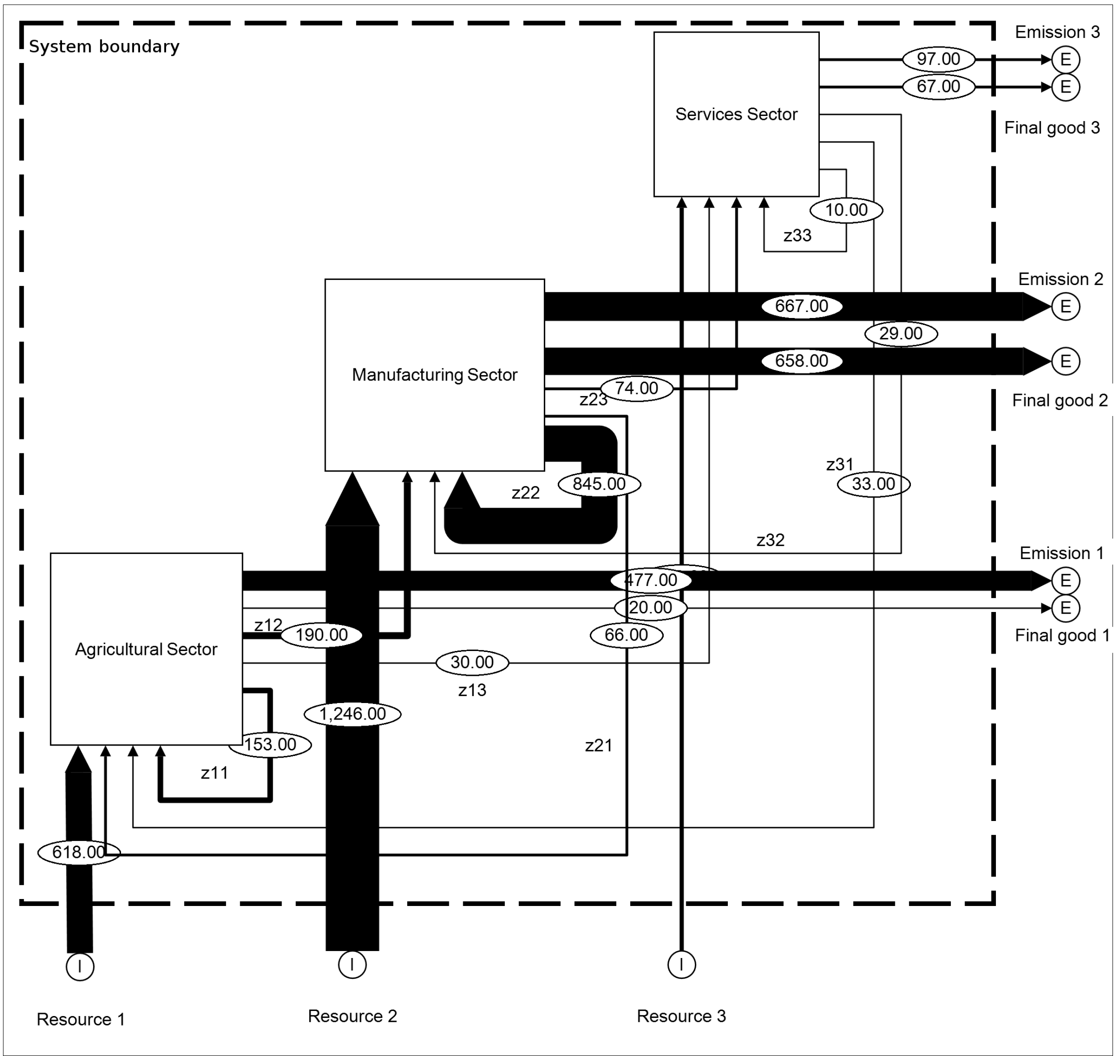

FIGURE 3.2: Flowchart with flows proportional to their value representing a three sector PIOT from table 3.4 (in million tons)

Flowcharts and sankey diagrams also have several limitations regarding the representation and assessment of the system structure. Even if the sectoral flow structure follows a predetermined configuration, e.g., in figure 3.2, the sectoral inflows are represented below the boxes representing each sector and the outflows on their right hand side, it is still difficult to visually identify whether flows are *external* or *internal*, because one needs to follow each flow to check whether it crosses the system boundary or not. Also, ideally, the sector would convey the value of the total sectoral throughput, which would then allow comparing each inflow and outflow contribution to the sectoral throughput. Another issue that hinders visual assessment is that the traditional linear arrangement of flows leads to multiple crossings of the flows, both between internal flows and between external and internal flows. This is especially an issue when the system entails cycling interactions, since cycling increases the number of crossings due to returning flows. All these issues can be found in figure 3.2 and also in conventional flowchart representations of material flows (Graedel et al., 2002; Spatari et al., 2002) and in Sankey diagrams representing multiple system components (Riehmann et al., 2005; Schmidt, 2005).

Ideally, a diagram would enable researchers to easily compare the *internal* and *external* flow structure, i.e. to assess the grade of intensity of flows (given visually by their relative size) and where they come and go to (given visually by their relative position). Flowcharts and Sankey diagrams perform well when assessing the relative size of flows. However, it is hard to identify *external* from *internal* flows and the position of the sectoral inflows and outflows is difficult to compare, since each flow needs to be followed to its source to know which flow it is. Thus, Sankey diagrams and flowcharts are not well suited for *disaggregated* visual structural analyses, i.e. structural analyses involving many flows.

2D coloured matrices provide a more orderly representation of the structure and avoid flow crossing. However, in a 2D matrix, patterns are hard to perceive because of the condensed matrix notation, where each internal (intersectoral) value, represents an input and output from different sectors at the same time. Therefore, it is hard to compare the input and output structure of a sector because it requires reading all cell values (colours) at the same time, either column-wise for the inflow structure or row-wise for the outflow structure. Additionally, human colour perception is not absolute, it is relative. In other words, it requires seeing two close colours simultaneously to be able to tell the difference. Therefore, it can be hard to recognise the colours associated to each pre-determined value in some cases, depending on the colour legend and the matrix pattern.

3D matrices use the third dimension to represent each cell value, usually as stacks, providing a more accurate reading than colours since all stacks are referenced to the same axis. However, 3D matrices require re-ordering to minimise the issue of high stacks on the front masking low stack at the back. Such issue also affects structural analysis since each matrix needs a different re-ordering depending on its values, making it difficult to compare the different matrix structures.

Thus, 2D and 3D matrices are not well suited to perform structural analyses comparing the sectoral linkages.

To sum up, three characteristics are required to perform visually structural analyses: 1. to identify the external and internal flows in a straight forward manner, 2. to identify inflows and outflows in a straight forward manner, 3. to identify the relative and absolute contribution of each flow to the total output of each sector. None of the previous visualisations satisfies all requirements simultaneously.

3.3.2 Circular diagrams representing systems with internal and external flows

Circular diagrams could constitute a visual representation satisfying the three conditions mentioned previously: 1. external and internal flows can be separated explicitly (internal flows represented in the inner part of the diagram and external flows in the outer part), 2. inflows and outflows can be identified by their position (e.g. the first 50% of flows are inflows and the second 50% of flows are outflows), and 3. the relative and absolute contribution of each flow can be represented by the width of the flow, which can be compared to the width of the total throughput of the sector.

In this subsection, two layouts for circular diagrams are proposed to represent systems with internal and external flows and avoid the issues described in the previous subsection: the contiguous and symmetrical layouts. Such diagrams would enable researchers to analyse visually the structure of the internal and external flows of a system in a disaggregated manner.

3.3.2.1 The contiguous layout

The bracketed numbers in the following explanation indicate a specific feature of the circular diagram; the same numbers are placed in figure 3.3 to help identify the corresponding diagram feature.

From a system's boundary perspective, there are two types of flows: the *external* ones, either entering or leaving the system's boundaries, and the *internal* ones, kept within the system's boundaries. The circular diagram can be drawn so that the *external* flows are represented in the *outer* part of the diagram [1], while the *internal* flows are represented in the *inner* part of the diagram [2]. So, the relative outer/inner position provides the visual cue to determine whether the flow is an external or internal one.

The key parts of the circular diagram are the segments representing each sector, which are positioned between the *external* and *internal* flows, hereafter called the *middle segments* [3]. These segments' lengths are proportional to the sectoral throughput. Therefore, the relative contribution of internal and external flows can be visually assessed by comparing the size of the flow to the size of the middle segment. Two axes are drawn along each *middle segment*, one with the absolute value of the throughput [4] and another as a percentage of the total sectoral throughput, from 0 to 100% [5]. These two axes enable researchers to determine the absolute and relative contributions of each flow against the throughput of the sector (i.e. its total inputs or outputs).

The external and internal inputs and outputs come and go to the same *middle segment*, so the segment must equal twice the total throughput and, since "what goes in, goes out", all inputs account for 50% of the *middle segment* while all outputs account for the other 50% [6]. The sectoral inputs are placed on the anti-clockwise half of the *middle segment* and the outputs are placed on the clockwise half. Note that the primary resources (which are inputs) are on the most anti-clockwise part of the middle segment while the final goods and emissions (which are outputs) are on the most clockwise part of the middle segment. Thus, the sectoral flows are ordered as follows, from anti-clockwise to clockwise: 1) external inputs (most anticlockwise, outer part), 2) internal input (anticlockwise, inner part), 3) internal outputs (clockwise, inner part) and 4) external outputs (most clockwise, outer part). Because the input and output flows of each sector are placed on the same *middle segment*, this type of circular diagram is called *contiguous*.

Each internal flow needs to connect two different middle segments only, since they represent the exchange flow between two sectors (e.g. of matter or energy). The internal flows are represented by *ribbons* and the size of both ribbon ends are proportional to the value of the flow; the rest of the ribbon is not necessarily proportional, e.g. a ribbon can get thinner in the middle to leave more space for other ribbons or to minimise crossing between ribbons. Instead of using an arrow head, each ribbon's end is carefully drawn to orient the ribbon: if the ribbon end touches the *middle segment*, it is an inflow [7]; if the ribbon does not touch the *middle segment*, it is an outflow [8]. In fact, this is a redundant visual cue since, as stated previously, the anti-clockwise half of the *middle segment* entails the inflows and the clockwise the outflows. However, this extra visual cue was introduced to help differentiate inflows from outflows. Self-loops can also be represented by a ribbon coming and going to the same middle segment [9].

The external flows do not need to be connected to another diagram part, so a simple "slice" instead of a ribbon is enough to determine its flow value. However, to make it possible to differentiate between the different input and output external flows, each of them is drawn on a different outer radius. In the current example, the following external flows have been drawn, from in to out: primary resources (external input) [10], final goods (external output) [11] and emissions (external output) [12].

So, the internal and external flows are represented slightly differently, but since their size conveys visually the value of the flows, it is possible to compare the *internal* and *external* flows between each other, and to the total throughput (represented by the *middle segment*). Thus, such configuration enables the researcher to perceive structural features, since the relative and absolute contribution of each flow to the total sectoral throughput can be established visually. For example, as shown in figure 3.3, in the agricultural sector, external inputs (i.e. primary resources) constitute 36% of its total throughput, while its

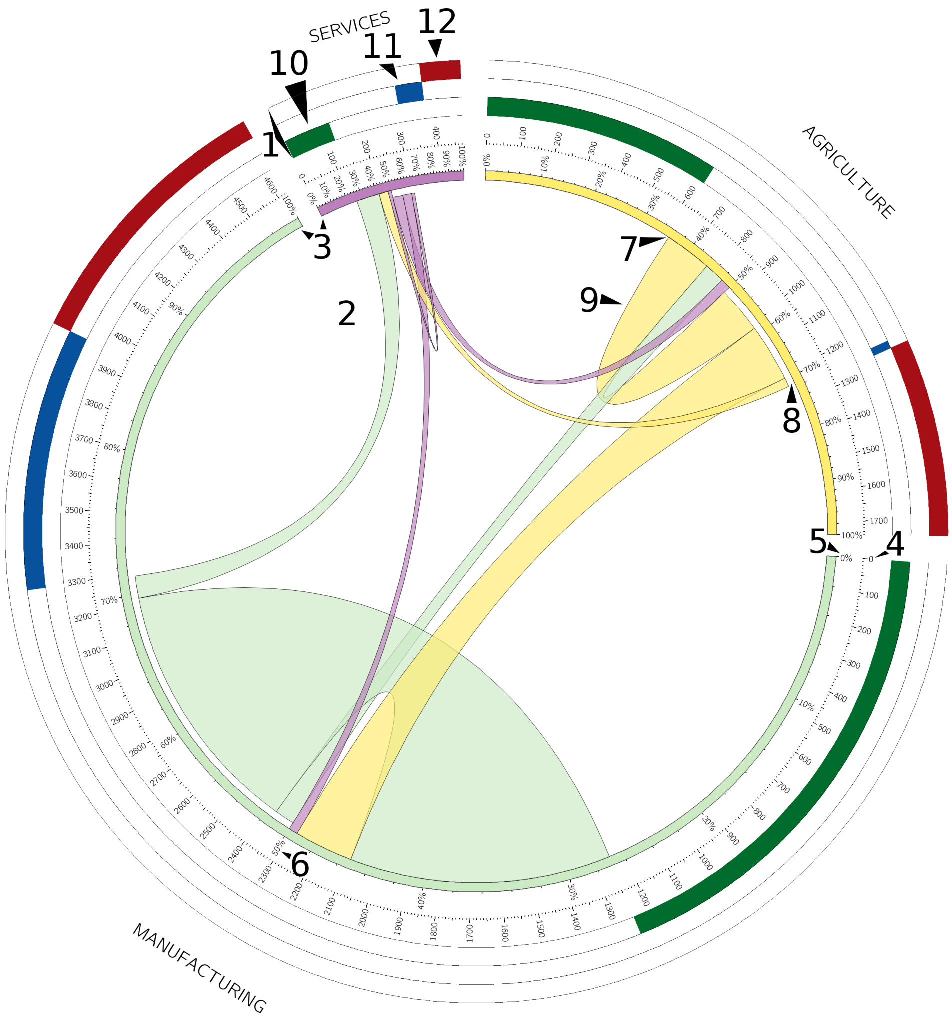

Figure 3.3: Non-normalised, contiguous circular diagram representing a three sector PIOT from table 3.4 (in million tons). Other characteristics: internal inflows sorted in decreasing order, ribbon colour matching the output sector, external flows (from in to out with colour code in brackets): primary resources (green), final goods (blue), disposals to nature (red). See text beginning at section 3.3.2.1 for the explanation of the numbered features.

external outputs (i.e. final goods and emissions) constitute about 28%. It can be deduced that part of the primary resources have been embedded in other sectors' final outputs and emissions.

The external and internal flows can be colour coded depending on the type of analysis to perform. Usually, the *middle segment* represents the colour identifying the sector: in figure 3.3, the agricultural sector is yellow, the manufacturing is green and the services is violet. Additionally, the *ribbons* are also colour coded. In figure 3.3, the internal outflows take this *middle segment's* colour. Also, the ribbons can be colour coded according to the sector they go to. The different colours of the outflows enables the researcher to identify patterns in the sectoral input structure (and when it is the inflows that are colour coded, then patterns can be identified in the output structure). The external flows are also colour coded according to the type of flow: the primary resources are green [10], the final goods are blue [11] and the emissions are red [12]. More sophisticated colour patterns have also been developed. For example, in figure 6.7 from chapter 6, each flow is coloured according to whether it belongs to the cyclic or acyclic structure. So, the flows that partially belong to both structures are split and coloured according to the structure to which they belong. Additionally, in this case, the middle segment does not represent the colour of the sector but it is also colour coded following the cyclic–acyclic colour code. Thus, the middle segment provides a visual cue of the contribution of the cyclic and acyclic structure to each total sectoral throughput.

Ribbons can also be ordered in decreasing or increasing order. In the current example, the internal inflows are sorted in decreasing clockwise order.

Thanks to the combination of colour code and ordering, patterns can easily be identified visually. For example, in figure 3.3, two patterns arise:

1. the services inputs (violet) is the minor contributor to the input structure of all three sectors (the last ribbon in the inflow ordering); and
2. the major input contributors in the agricultural and manufacturing sectors are self-loops (the first ribbon in the inflow ordering, which has the same colour as the middle segment).

Thus, the *middle segments* constitute the key part of the diagram because:

1. they indicate each sectors' position.
2. the *external* and *internal* input and output flows are ordered in relation to the middle segment and, thus, middle segments provide a visual cue to which all other input and output flows of the sector can be compared, both in size and in position.

3.3.2.2 The symmetrical layout

An alternative configuration where the input and output flows of each sector are represented separately on two symmetrically opposed middle segments is drawn in figure 3.4. The bracketed numbers of the following description help identify the corresponding features on the figure. This configuration is called *symmetrical* because two middle segments are used to represent each sector, one opposed to the other, following an imaginary vertical, symmetrical line [1]; the middle segments on the left-hand side account for the the external and internal inputs [2], and the middle segments on the right-hand side account for the external and internal outputs [3]. The other features of the *symmetrical* layout are the same as the *contiguous* one, and it can be customised also using the same options (e.g. ribbon ordering and colour pattern).

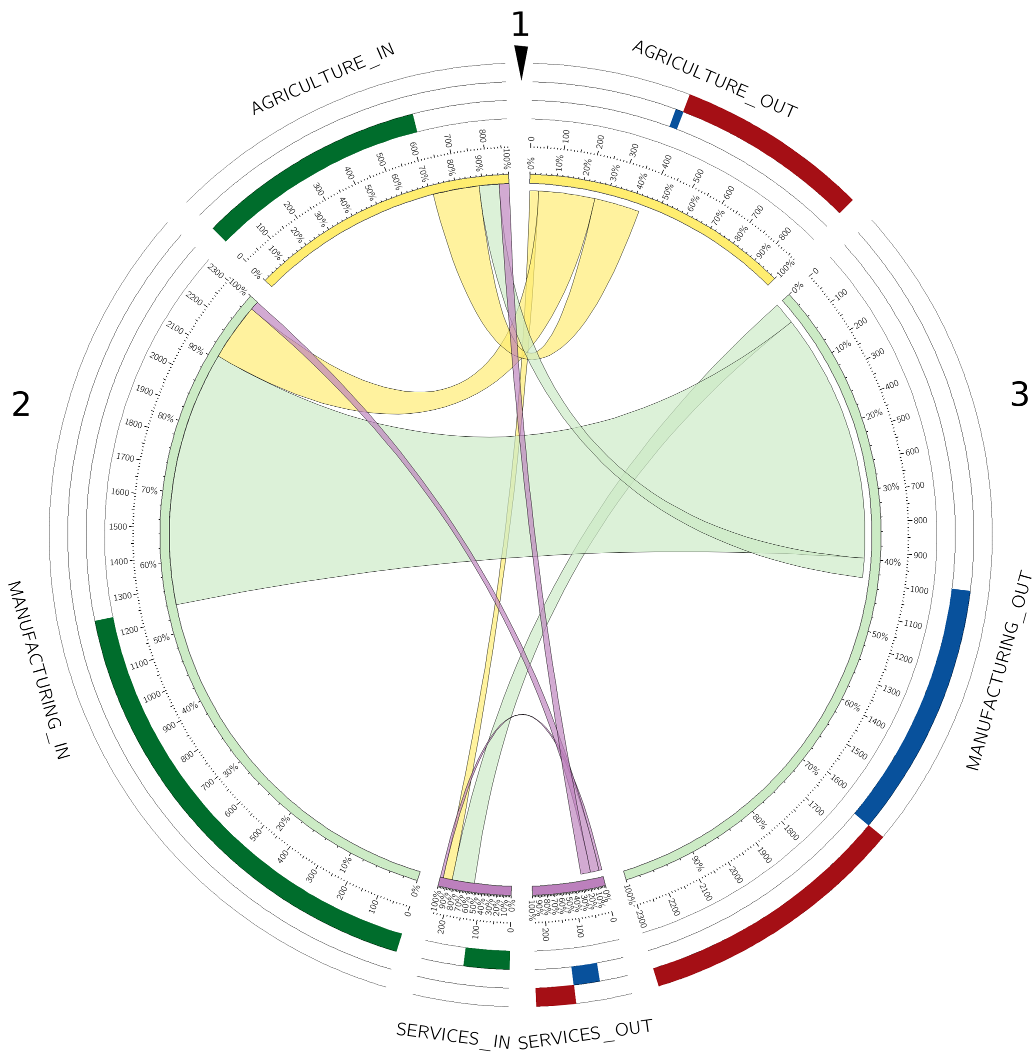

FIGURE 3.4: Non-normalised, symmetrical circular diagram representing a three sector PIOT from table 3.4 (in million tons). Other characteristics: internal inflows sorted in decreasing order, ribbon colour matching the output sector, external flows (from in to out with colour code in brackets): primary resources (green), final goods (blue), disposals to nature (red). See text beginning at section 3.3.2.2 for the explanation of the numbered features.

The main differences between the *contiguous* and *symmetrical* layouts are that:

1. the middle segment in a *contiguous* layout equals twice the total throughput (corresponding to $2 \cdot \underline{x}$ in the IO jargon) while in the symmetrical layout it equals the total throughput (corresponding to $\underline{x}$).
2. since in the symmetrical layout all segments with input flows are placed on the same side, it is easier to compare the input structures; the same applies for the output structures.

The circular diagram layouts developed in this section have been drawn with Circos, an open source software originally designed to draw the human genome (Krzywinski et al., 2009). This software has been chosen because, although it has not been thought to represent systems with internal and external flows, it is the most customisable software drawing circular diagrams since it supports a wide array of data representation layouts. However, standard layouts matching the *contiguous* and *symmetrical* layouts described above did not exist, so the *contiguous* and *symmetrical* layouts had to be programmed specifically into a new function, including the different customisable options. Additionally, Circos does not provide any tool to parse data matching the IOT format, so another function had to be programmed to parse the PIOT data into the Circos format. Both functions have been integrated in Metab-X, an open source software developed in this research to perform the structural decomposition devised in chapter 4 and indicators developed in chapter 5 (c.f. appendix C).

Finally, another layout option is to normalise the sectoral flows. This option is key for structural analyses since it enables the researcher to assess the relative contribution of each flow. This is important because some sectors might seem to generate few emissions in absolute terms while in reality they generate proportionally more emissions than the other sectors. If this sector increases its activity, its emissions will surpass the others. This type of diagram is called a *normalised* diagram, as opposed to the diagram representing the actual values, which is called *non-normalised*. Note that in *normalised* diagrams, *ribbons* can have different end sizes since each sector is normalised by its own total throughput, so each sector scale is usually different; in *non-normalised* diagrams, both ribbon ends have always the same size since all sectors use the same scale. *Symmetrical* and *contiguous* diagrams can either be *normalised* or *non-normalised*.

The different layouts (i.e. *symmetrical* or *contiguous*) and features of the circular diagram (e.g. representation to scale of the sectoral throughput, colour code and ordering of the ribbons (internal flows) and normalisation of the flows) enable researchers to perform structural analyses visually. This type of circular diagrams even makes it possible to perform visually structural analyses that usually require algebraic calculations. To illustrate this point, the next section shows how to accomplish visually a backward and forward linkage analysis.

3.3.3 Visual direct backward and forward linkage analysis

Recalling the direct backward analysis performed in section 3.2.4.2, the direct backward linkage measures are the column sum of the technical coefficient matrix (c.f. equation 3.38). Following this equation, the direct backward linkages of sector j (BL_j^{direct}) can also be defined as:

$$BL_j^{direct} = \frac{\sum_{i=1}^{n} z_{ij}}{\underline{x}_j} \tag{3.51}$$

Thus, the BL_j^{direct} values are given by the contribution of all sectoral inputs (their sum) to the total sectoral throughput; in other words, the BL_j^{direct} values are characterised by the percentage contribution of the sectoral inputs to the sectoral throughputs. This measure can easily be assessed in symmetrical circular diagrams since the middle segment is proportional to $\underline{x}_j$ and all internal inflows are grouped together. Thus, the BL_j^{direct} values can directly be read from the percentage sectoral axis and equals the value where the internal inputs end. A new symmetrical, normalised diagram is drawn in figure 3.5 to perform this analysis because the *normalised* view helps in comparing the proportions of each sector's internal inflow and outflow structure, since in the normalised layout all sectors have the same (normalised) size. However, in this case, the non-normalised diagram can also provide the desired information since it is also symmetrical and, thus, the sectoral inputs and outputs are related to $\underline{x}$ and the scale also provides percentage information.

The direct backward linkages match the ones calculated analytically in section 3.2.4.2. The following BL_j^{direct} can be read from figure 3.5; note that the percentage value needs to be subtracted from 100 since it is the contribution of the internal flows that is sought, not the contribution of the external flows:

- $BL_{agricutural}^{direct} = 100\% - 71\% = 29\%$
- $BL_{manufacturing}^{direct} = 100\% - 54\% = 46\%$
- $BL_{services}^{direct} = 100\% - 52\% = 48\%$

These results match the ones of table 3.5. Note they correspond to the direct backward linkage values of the *complete physical structure* and are totally different from the direct backward linkage values of the *goods-only physical structure*. This reinforces the interpretation of the different structures discussed in section 3.2.4.1, since the direct backward linkages of the structure represented in figure 3.5 correspond precisely to the ones found for the *complete physical structure*.

Additionally, the same diagram can be used to find the direct forwards linkages of each sector FL_j^{direct}. These are calculated as the row sum of the technical coefficients matrix of the input-driven model ($\underline{\mathbf{B}}$), which is different from the technical coefficients matrix used previously ($\underline{\mathbf{A}}$), which corresponds to an output-driven model one. According to Miller and Blair (2009), direct forwards linkages are defined as

$$FL_i^{direct} = \sum_{i=1}^{n} b_{ij} \tag{3.52}$$

where

$$\underline{\mathbf{B}} = \hat{\underline{\mathbf{x}}}^{-1} \cdot \mathbf{Z} \tag{3.53}$$

So, FL_j^{direct} can also be related to the intersectoral output flows, i.e. to the internal outflows of the circular diagram:

$$FL_i^{direct} = \frac{\sum_{j=1}^{n} z_{ij}}{\underline{x}_i} \tag{3.54}$$

Thus, the FL_i^{direct} are given by the contribution of all intersectoral outputs (their sum) to the total sectoral throughput; in other words, the FL_i^{direct} is the percentage contribution of the intersectoral outputs to the sectoral throughput. This measure can easily be found in symmetrical circular diagrams since the middle segment is proportional to $\underline{x}_i$ and all internal outflows are grouped together. The direct forward linkages can be read from figure 3.5 (the same ones can also be read from figure 3.4):

- $FL_{agricutural}^{direct} = 43\%$
- $FL_{manufacturing}^{direct} = 43\%$ (coincidentally)
- $FL_{services}^{direct} = 30\%$

So, the circular diagrams devised in this section can be used to perform aggregated structural analyses visually, such as the backward and forward linkage analysis. But more importantly, these circular diagrams help in identifying structural patterns at a disaggregated level, enabling researchers to better understand the structure of the economic system. For example, by assessing the contribution of particular flows to the (aggregated) backward and forward linkage measures.

Circular diagrams will be used in chapter 6 to assess the structural relevance of the cyclic intersectoral flows in an illustrative example and to help identifying which flows are to be modified to improve the overall resource efficiency of the economic system. The significance of the circular diagrams will be discussed afterwards, in section 7.3 of the conclusion chapter.

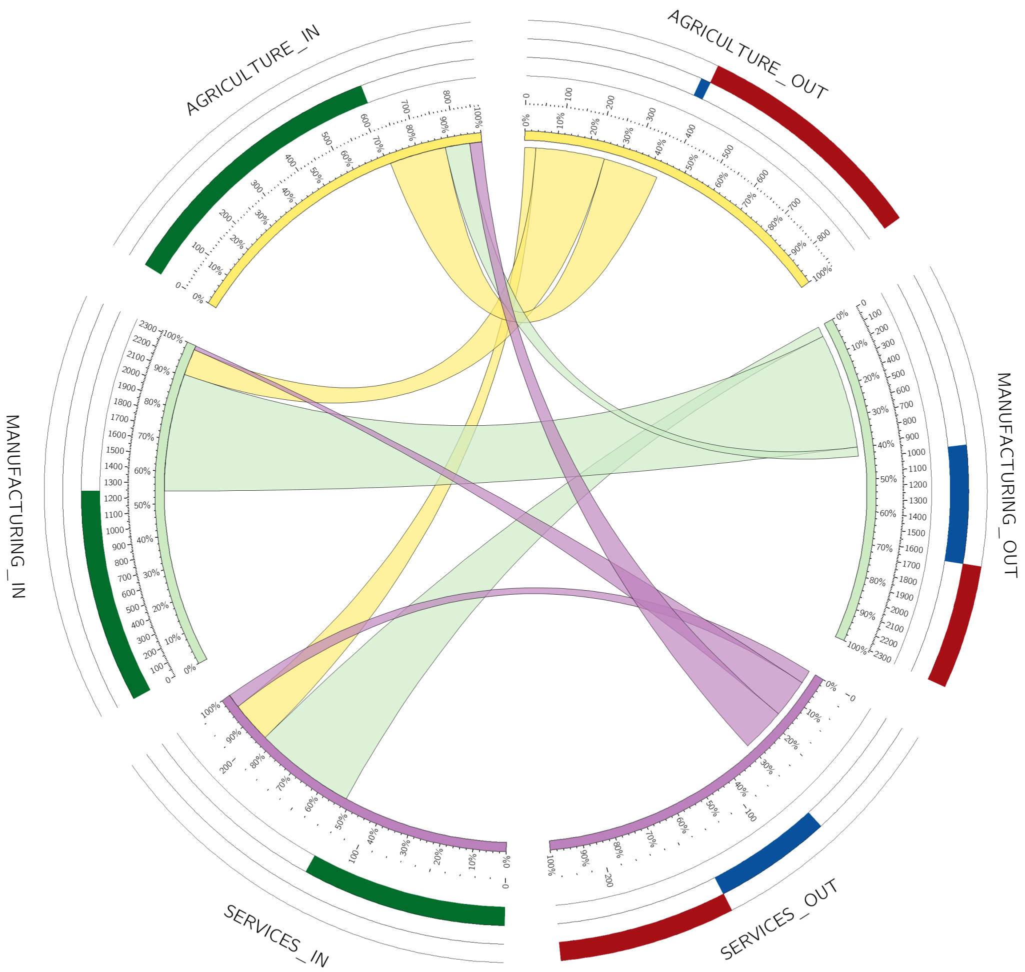

FIGURE 3.5: Normalised, symmetrical circular diagram representing a three sector PIOT from table 3.4 (in million tons). Other characteristics: internal inflows sorted in decreasing order, ribbon colour matching the output sector, external flows (from in to out with colour code in brackets): primary resources (green), final goods (blue), disposals to nature (red).

Chapter 4

Identifying the full cyclic structure of the economic system

4.1 Introduction

As reviewed in section 2.6, cycling has been identified as a key structural component of complex dissipative systems such as the economic system or trophic food webs (i.e. a network representing the feeding connections within an ecosystem), affecting some of the system properties: cycling increases residence time of materials or energy (Herendeen, 1989), acts as a buffer for fluctuations in energy supply (Loreau, 1994) and augments the stability of the system (DeAngelis et al., 1989).

Measuring cycling in trophic food webs has focussed at system-level, measuring aggregately the cycling happening within the system (Finn, 1976). This measure has also been applied to understand industrial systems (Bailey et al., 2008), which are dissipative systems as trophic food webs (Suh, 2005; Bailey et al., 2008). However, typically, the study of cycling in industrial systems has been more focussed at process-level rather than system level (Bailey et al., 2008), i.e. studying recycling happening at a specific point (sector) of the economic system.

However, despite the availability of numerous cycling indicators (Bailey et al., 2008), the complete structure of cycling has never been revealed. In other words, the primary resources and emissions exclusively due to cycling have never been identified for a dissipative system. Previous indicators had quantified the amount of cycling through a specific sub-system component (sector) (Bailey et al., 2008), through the whole system with an aggregate measure (Finn, 1976), and others methods found the inter-sectoral component of the cyclic structure (Ulanowicz, 1983). Consequently, the relationships established between these partial cyclic structures and the system's behaviour were limited, since the full cyclic structure was unknown.

Therefore, this chapter aims to identify the full cyclic structure of the economic system, i.e. to identify the inter-sectoral cycling plus the resources and emissions associated to that cycling.

First, the current available method to calculate inter-sectoral cycling is reviewed in section 4.2. It is found that it is computationally limited and a new algorithm that removes this restriction is suggested in section 4.2.1. Also, in section 4.2.2, it is found that the previous algorithm overestimates the amount of cycling when applied to a conventional IOT and that a previous, product-based decomposition is required. Such product-based decomposition is developed for the case of PIOTs in section 4.3.

Then, the next step is to identify the resources and emissions associated to inter-sectoral cycling. Section 4.4 develops a method for that purpose. It is found that two types of cycling exist — pre-consumer cycling and post-consumer cycling —, and it is mathematically demonstrated that they have opposite effects regarding the resource efficiency of the system. This opens the possibility to improve the resource efficiency of the system by altering its structure.

Finally, section 4.5 is interested in identifying the cyclic structure of the economy. However, when it comes to decompose the system structure between the cyclic part and its acyclic counterpart, it is found that such decomposition is not trivial, as suggested in previous literature. The structure of the cyclic component has in fact a direct and an indirect sub-components and so does the acyclic component. Therefore, the structure of the economy can in fact be decomposed between its cyclic and acyclic sub-structures or between its direct and indirect sub-structure. The issue is that these two sets of sub-structures are in fact intertwined.

In section 4.5.1 it is first explain the rationale behind each of these sub-structures (cyclic-direct, cyclic-indirect, acyclic-direct and acyclic-indirect) and their algebraic notation is presented for the case of a PIOT.

Then, in section 4.5.2, a new method to identify each of the sub-structural components is developed.

So, section 4.5 constitutes the main advancement of this thesis, since it provides a new understanding of how the structure of the economy works and develops a method to identify each of the newly identified sub-structural components. Thus, this chapter is a methodological chapter which also brings new theoretical understanding on the functioning on the physical structure of the economic system.

Note that, as in the previous chapter, the term *disposals to nature* refers to all material flows that the economy releases back to the environment and it can be used interchangeably with the terms *waste* and *emissions*.

4.2 Calculating the cyclic intersectoral matrix

4.2.1 New algorithm to extract all simple cycles from an Input-Output Table

Ulanowicz (1983) devised an algorithm to identify intersectoral cycling that requires listing all simple cycles. He argued that this would not be an issue for ecological networks since they are usually quite sparse and thus contain few cycles (Ulanowicz and Kay, 1991). This is not the case for economic systems where IOTs tend to be complete (i.e. most of the elements of the matrix are non-null). In this case, listing all cycles becomes an issue.

An IOT is a digraph[1] and the number of simple cycles within a complete digraph[2] with n nodes are, according to Johnson (1975):

$$\sum_{i=1}^{n} \binom{n}{n-i+1} \cdot (n-i)! \tag{4.1}$$

This means that the number of cycles of a complete digraph increases at factorial rate. For example, a complete digraph as small as 11 nodes (e.g. representing a PIOT with 11 sectors) has about 11 million different simple cycles; a 12 sector IOT has 115 million and a 13 sector IOT has 1400 million.

Enumerating all cycles for a 12 nodes complete digraph fails on a 32-bit computer[3] because the result array is too big to be stored in the Random Access Memory (RAM). Usually, IOTs are bigger than 11 sectors and having to aggregate any IOT down to 11 sectors would be analytically restrictive. Thus, the original Ulanowicz (1983) algorithm is restricted by current computational capacity[4].

[1] A graph is an abstract representation of a network, where the network components, called nodes or vertices, are connected by arcs (also called edges). A digraph is a directed graph , i.e. a graph where the arcs between nodes are oriented. An IOT is thus a digraph since the exchanges between the economic sectors are oriented (the flow from sector A to B is usually different than the flow from sector B to A).

[2] A complete digraph is a digraph containing all possible connections between its nodes, so the intersectoral matrix is a complete digraph when all a_{ij} are non null

[3] A memory error was triggered when using the Johnson (1975) algorithm implemented in the NetworkX 1.6 (Hagberg et al., 2008).

[4] More sophisticated computers, for example with 64-bit technology, can handle bigger arrays in RAM but also run out of RAM for a similar array size since the number of cycles increase at factorial rate.

Below, two improvements are suggested so that the algorithm consumes less computational resources (RAM), making it possible to study complete digraphs of any[5] size.

The first improvement restricts the number of cycles that need to be treated at once by treating only the cycles of the nexus[6] containing the weakest link (i.e. the weakest arc or edge) of the digraph. The improvement consists on working only on the cycles constituting the nexus with the weakest arc by finding the weakest arc of the graph and checking if any simple cycle passes through it. If so, the weakest arc of the graph is also the weakest arc of the nexus defined by itself, i.e. of all cycles passing through it. Since only the cycles passing through a specific arc are identified, the result array containing the cycles is smaller. Unfortunately, since the amount of cycles increases at factorial rate, this first improvement is not enough to avoid memory issues when dealing with big arrays.

The second improvement avoids storing all cycles as an array, which is what ultimately causes the memory overflow[7]. The second improvement consists of avoiding the storage of all identified cycles by implementing the Johnson (1975) algorithm as a generator function[8], i.e. returning a cycle at a time. Since the cycles are not stored, the Johnson algorithm is run twice to perform all required calculations. The information required to allocate the weight of the weakest arc of the nexus between all cycles composing it is the circuit probability of each cycle and the sum of the circuit probabilities of the nexus. So, a first search of all cycles passing through the weakest arc (identified in the previous paragraph) enables to calculate the sum of the circuit probabilities of the nexus, which is the only number stored. Then, a second search of the cycles is run to allocate the weight of weakest arc of the nexus between all cycles composing the nexus which are then subtracted from the original array.

To summarise, the suggested algorithm has the following steps:

1. Identify the weakest arc of the graph [the smallest intersectoral coefficient] and check whether any cycle passes through it. If no cycle is found, start again on the next weakest arc; if any cycle is found, continue.

[5] The improved algorithm poses no computational restriction but it can be extremely time consuming, depending on the intersectoral matrix size and computational speed.

[6] Nexus is a set of simple cycles sharing a link.

[7] Note that storing the results array in the hard-drive to free the RAM is neither a good solution since this process is extremely time consuming (more than recalculating all cycles) and the arrays containing all cycles are huge (about 400 MB for each 10 million cycles) which could also lead to hard-drive memory shortage.

[8] A generator function returns an iterator (i.e. a single value at a time), while a normal function returns all values at once. For programming languages that do not have generator functions, the Johnson (1975) algorithm can be implemented twice in the body of the algorithm including the required intermediate calculations.

2. Iterate over all cycles passing through the weakest arc, calculate their circuit probability and add it to this nexus probability sum (the only number stored).
3. Iterate over all cycles passing through the weakest arc, calculate their circuit probability and use the previously calculated nexus probability to allocate the weight of the weakest arc amongst all cycles composing the nexus and subtract it from the original array.
4. Iterate over the remainder array until all cycles are removed.

At this point, all cycles from the original intersectoral matrix are identified and quantified, resulting in the cyclic intersectoral matrix $\mathbf{Z}^c$. Both the algorithm suggested by Ulanowicz (1983) and the new one gather the same results. The difference is that the new algorithm can be applied to IOTs of any size while the previous one would cause a memory overflow for big matrices, especially for complete ones. The new algorithm has been programmed in python, using the NetworkX library (Hagberg et al., 2008), and included in the Metab-X package, a software developed to perform the structural decomposition developed in this thesis; see appendix C for further details on Metab-X.

4.2.1.1 Numerical example

The intersectoral matrix of the PIOT presented in section 3.2.2.3 (chapter 3) and represented in table 3.4 is decomposed into its corresponding cyclic and acyclic[9] matrices.

When computing the decomposition, the Johnson (1975) algorithm recognised eight different simple cycles (numbers represent the nodes (sectors) through which each cycle goes through): 1-1, 2-2, 3-3, 1-2-1, 1-2-3-1, 1-3-2-1, 2-3-2 and 1-3-1, i.e. all possible cycles of a complete three nodes digraph. Using either of the Ulanowicz (1983) algorithms or the new one suggested in section 4.2.1, the results below are found. Recall equation 2.41 where Ulanowicz (1983) stated that the total intersectoral flows ($\mathbf{Z}$) are either cyclic ($\mathbf{Z}^c$) or acyclic ($\mathbf{Z}^a$). Note that the simple cycles cannot be discerned from each other once re-aggregated as $\mathbf{Z}^c$.

$$\mathbf{Z}^c = \begin{pmatrix} 153 & 69 & 30 \\ 66 & 845 & 32 \\ 33 & 29 & 10 \end{pmatrix} \tag{4.2}$$

$$\mathbf{Z}^a = \begin{pmatrix} 0 & 121 & 0 \\ 0 & 0 & 42 \\ 0 & 0 & 0 \end{pmatrix} \tag{4.3}$$

[9] In section 4.5.1.2, it is argued that the acyclic intersectoral component identified with the algorithm ($\mathbf{Z}^a$) is in fact an indirect intersectoral component ($\mathbf{Z}^{ind}$), not only acyclic.

4.2.2 The need of a disaggregated, product-based approach to identify the cyclic structure

The cyclic decomposition of the intersectoral matrix presented in the previous section follows the work of Ulanowicz (1983). However, applying it to a dissipative system which actually represents the simultaneous production of several final products (e.g. the production structure of the economic system, or even a food web with different trophic levels) is in fact misleading.

What have made the results suspicious is that, in principle, each sector requires intermediate production from the other sectors to produce final goods, even if in small quantities. This implies that z^a_{12}, z^a_{13}, z^a_{21}, z^a_{23}, z^a_{31} and z^a_{32} should be positive values. However, the acyclic matrix $\mathbf{Z}^a$ from the numerical example only contains two positive values, z^a_{12} and z^a_{23} (c.f. equation 4.3).

This is due to the way the algorithm identifies and extracts cycles, in particular because the cyclic matrix is calculated before the acyclic one. The proof is simple: if all acyclic flows mentioned above are considered simultaneously, they constitute cycles and are recognised as such by the algorithm. Thus, applying either the Ulanowicz algorithm (Ulanowicz, 1983) or the new algorithm (c.f. section 4.2.1) to extract the cycles of the intersectoral matrix of a PIOT representing the simultaneous production of several final products will systematically gather misleading results.

The solution requires treating the production structure of each final product separately so that the acyclic flows can be identified as such in each case and not mistaken as cyclic ones. In other words, the solution requires applying the algorithm to each of the n structures producing the n final goods — hereafter called the *product-based structures* — and, then, re-aggregating them all to find the cyclic and indirect intersectoral matrices of the aggregated structure.

The method to decompose a PIOT into its *product-based structures* is developed in section 4.3. A full numerical example with a simpler cyclic structure is provided below to illustrate how identifying the cycles in a aggregated structure lead to misleading results.

4.2.2.1 Numerical example

A hypothetical structure with 3 sectors is presented in figure 4.1 and table 4.1.

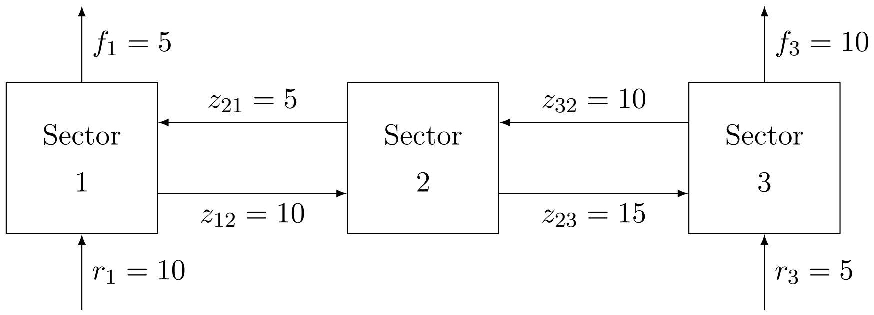

FIGURE 4.1: Hypothetical three compartment system with cycling and two final outputs. r_i are primary resources, z_ij are intersectoral flows and f_i are final outputs.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	10	0	5	15
Sector 2	5	0	15	0	20
Sector 3	0	10	0	10	20
Resources	10	0	5		
Total inputs	15	20	20		

TABLE 4.1: IOT representing a hypothetical three compartment system with two simple cycles and two final outputs

By visual exploration of either figure 4.1 or table 4.1, only two simple cycles[10] are identified: a cycle between sector one and two of value 5 (the lower value of the reciprocally exchanged flows) and another one between sector two and three of value 10 (the lower value of the reciprocally exchanged flows). The total amount of cycling can be measured as the total inter-sectoral flows involved in cycling and can be called as "cyclic Total System Throughput" (TST_c) as suggested by Finn (1976). In this particular case, $TST_c = 5 + 5 + 10 + 10 = 30$.

Now, the structure is decomposed in its *product-based* structures[11], i.e. the structures representing the flows required to produce each final good. Here, only two *product-based* structures are calculated since the original structure only produces two final outputs (by sector 1 and 3). Tables 4.2 and 4.3 represent the intermediate flows and primary resources required to produce the final outputs of sector one and sector three respectively. If both tables are added, the original IOT in table 4.1 is found.

A visual exploration of table 4.2 reveals that the cycle between sectors one and two caused by the production of final good one is of 1.818 units (lowest value between 1.181 and 2.273) and the cycle between sectors two and three caused by the production of final

[10] A simple cycle is a cycle only passing once through each sector, i.e. not entailing any sub-cycle within it.

[11] The mathematical formulation and relationships between the product-based structures for PIOTs is presented in section 4.3. The same method can be applied to MIOTs using the traditional Leontief quantity model (Leontief, 1941).

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	1.818	0	5	6.818
Sector 2	2.273	0	1.364	0	3.636
Sector 3	0	1.818	0	0	1.818
Resources	4.545	0	0.455		
Total inputs	6.818	3.636	1.818		

TABLE 4.2: IOT representing the flows required for the final production of sector one of the system represented in figure 4.1

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	8.182	0	0	8.182
Sector 2	2.727	0	13.636	0	16.364
Sector 3	0	8.182	0	10	18.182
Resources	5.455	0	4.545		
Total inputs	8.182	16.364	18.182		

TABLE 4.3: IOT representing the flows required for the final production of sector three of the system represented in figure 4.1

good one is of 1.364 units (the lowest value between 1.364 and 1.818). So, producing 5 units of final product 1 induces a $TST_c = 1.818 + 1.818 + 1.364 + 1.364 = 6.364$.

Similarly, a visual exploration of table 4.3 reveals that the cycle between sectors one and two caused by the production of final good three is of 2.727 units (lowest value between 2.727 and 8.182) and the cycle between sectors two and three caused by the production of final good three is of 8.182 units (the lowest value between 8.182 and 13.636). So, producing 5 units of final product 1 induces a $TST_c = 2.727 + 2.727 + 8.182 + 8.182 = 21.818$.

So the total amount of cycling happening due to both structures is $TST_c = 6.364{+}21.818 = 28.182$, which is lower than the value (30) found by exploring the aggregated structure of table 4.1. This difference can be understood by applying the same reasoning developed in this section (4.2.2): acyclic flows that belong to different product-based structures can be mistaken by cyclic flows when the different product-based structures are aggregated.

In this particular case, this becomes clear when analysing the cyclic structure of the two different product-based structures. For example, on the one hand, the cycling happening between sectors one and two of the two product-based structures add up to $1.818 + 2.727 = 4.545$, generating a $TST_c = 9.09$; similarly, the cycling happening between sectors two and three is $1.364 + 8.182 = 9.545$, generating a $TST_c = 19.09$.

On the other hand, the analysis of the aggregate structure revealed a cycle of 5 units between sectors sectors one and two, generating a $TST_c = 10$, overestimating the actual value of $TST_c = 9.09$. Similarly, the other cycle between sectors 2 and 3 was of 10 units generating a $TST_c = 20$, also overestimating the actual value of $TST_c = 19.09$.

Below, the cycles are extracted from the main array of both product-based structures so as to obtain the acyclic flows (according to Ulanowicz (1983)).

For instance, table 4.2 becomes table 4.4, revealing an acyclic flow of 0.455 from the primary resource three to sector three to sector two to sector one to final output one; in addition to the acyclic flow of 4.545 extracted and transformed directly in final output by sector one.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	0	0	5	5
Sector 2	0.455	0	0	0	0.455
Sector 3	0	0.455	0	0	0.455
Resources	4.545	0	0.455		
Total inputs	5	0.455	0.455		

TABLE 4.4: IOT representing the acyclic flows required for the final production of sector one of the system represented in figure 4.1

Similarly, table 4.3 becomes table 4.5, revealing an acyclic flow of 5.455 from the primary resource one to sector one to sector two to sector three to final output three; in addition to the acyclic flow of 4.545 extracted and transformed directly in final output by sector three.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	5.455	0	0	5.455
Sector 2	0	0	5.455	0	5.455
Sector 3	0	0	0	10	10
Resources	5.455	0	4.545		
Total inputs	5.455	5.455	10		

TABLE 4.5: IOT representing the acyclic flows required for the final production of sector three of the system represented in figure 4.1

However, if tables 4.4 and 4.5 were added to obtain the aggregated structure, two new simple cycles would be identified: a cycle between sector 1 and 2 of value 0.455 ($TST_c = 0.91$) and a cycle between sector 2 and 3 of the same value. Precisely, these values correspond to the differences found between the cyclic structure identified at aggregated level and the cyclic structure identified by analysing each product-based structure independently. Therefore, it has been proven that identifying the cyclic structure at aggregated level overestimates the cyclic structure since it mistakes acyclic flows by cyclic ones.

4.2.3 Finn's Cycling Index' limitations

Since the algorithm developed by Ulanowicz (1983) and the metric suggested by Finn (1976) to measure the amount of cycling do not match (c.f. end of section 2.6.5.4) and, as revealed by the previous section, the algorithm developed by Ulanowicz (1983) overestimates cycling systematically, the Finn Cycling Index is reviewed in depth in this section. The idea is to ascertain whether it quantifies cycling appropriately and, if so and if possible, use it to develop a method to find the disaggregated cyclic structure of the economic system.

Finn (1976) analyses the cyclic structure of a simple system, here reprinted in figure 4.2, to start elaborating the theoretical foundations of his method. Finn identified a cycle between sector two and three of 5 units, gathering according to his notation a cyclic Total System Throughput TST_c of 10 (5 per sector involved). This cycle can also be found by visual exploration: since $F_{23} = 5$ and $F_{32} = 15$, the cycle throughput is given by the lowest exchanged flow, which acts as a cycle bottleneck — the difference being diverted elsewhere (as final output $y_{03} = 10$ in this case).

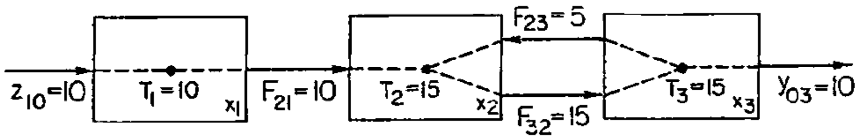

FIGURE 4.2: Hypothetical three compartment system with cycling (Finn, 1976, fig. 1b).

Then, Finn (1976) developed a more general method to identify the amount of cycling happening within the system; the main feature of the method is summarised in equation 2.38 (page 78). The idea is that the diagonal elements of the Leontief inverse matrix (or transition closure matrix, as called in ecological IOA) contain information about the level of cycling through each sector. In particular, Finn (1976, pg. 373) stated that: "TST_c [i.e., the total amount of cycling through the system] can be found by eliminating all terms in $(\mathbf{I} - \mathbf{Q})^{-1}_{ii}$ [i.e. the equivalent to the Leontief inverse] not due to cycling [i.e. subtracting 1 to the diagonal elements and zeroing the rest of elements], multiplying the resulting matrix by the outflow vector and summing the elements of the resulting vector". However, this approach poses several issues and limitations.

First, this method cannot be applied to systems where some sectors do not generate final outputs because the level of cycling of these sectors will be "ignored" by definition. According to Finn (1976), the excess of 1 of each diagonal element of the Leontief inverse matrix indicate the amount of cycling in that sector due to producing one final unit of the same sector (as stated in equation 2.38). Therefore, if a given sector does not produce any amount of final output, the cycles passing through it will be not computed in the algebraic calculation of TST_c.

This can be corroborated for the example provided by Finn himself, here presented in figure 4.2; the corresponding IOT is presented in table 4.6.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	10	0	0	10
Sector 2	0	0	15	0	15
Sector 3	0	5	0	10	15
Resources	10	0	0		
Total inputs	10	15	15		

Table 4.6: IOT representing the flows in figure 4.2

The Leontief inverse corresponding to table 4.1 is

$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 1.5 & 1.5 \\ 0 & 0.5 & 1.5 \end{pmatrix} \tag{4.4}$$

So, according to equation 2.38, sector one generates no cycling per unit of its final outflow, sector two generates 0.5 units of cycling per unit of its final outflow and sector three generates 0.5 units of cycling per unit of its final outflow. So, when multiplied by the final output vector, only the cycling associated to sector 3 will be captured, as follows:

$$TST_c = \mathbf{i}' \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.5 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix} = \mathbf{i}' \cdot \begin{pmatrix} 0 \\ 0 \\ 5 \end{pmatrix} = 5 \tag{4.5}$$

In this sense, this method ignores the amount cycling generated by sector 2 which, according to Finn's own explanation (see above) should also be accounted into TST_c (the TST_c calculated manually was 10).

Second, as a consequence of the first limitation, the level of cycling associated to each product-based structure cannot be determined — only the level of cycling for the aggregated structure. Since a product-based structure represents the system structure associated to the production of a single given final output, the rest of the final outputs is null. Therefore, Finn's method could not be applied to these particular cases. This poses a serious analytical restriction, since while the total amount of cycling can be determined, it cannot be established which is the final product that induces most cyclic interactions.

Third, the method does not seem to be robust for more complex systems. For instance, as noted in section 2.6.5.4, Ulanowicz and Finn's methods gather quite different results. Another counter-example is developed below to test the reliability of Finn's method.

Figure 1b in Finn (1976) was expanded into figure 4.1 (represented in table 4.1) by including an acyclic flow of 5 units entering sector 3, going through sector 2 and exiting through sector 1. This additional flow generated an additional simple cycle compared to figure 4.2. The new example is presented in table 4.7 and includes a 1 unit flow entering sector 2 and leaving sector 2. This does not generate any additional cycle but allows the application of Finn's method to calculate the systemic cycling (no final output will be null).

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	10	0	5	15
Sector 2	5	0	15	1	21
Sector 3	0	10	0	10	20
Resources	10	1	5		
Total inputs	15	21	20		

TABLE 4.7: IOT representing a hypothetical three compartment system with two simple cycles and three final outputs

The Leontief inverse matrix corresponding to table 4.7 is:

$$\begin{pmatrix} 1.33 & 0.98 & 0.74 \\ 0.69 & 2.07 & 1.55 \\ 0.33 & 0.98 & 1.74 \end{pmatrix} \tag{4.6}$$

So, according to equation 2.38, sector one generates 0.33 units of cycling per unit of its final outflow, sector two generates 1.07 units of cycling per unit of its final outflow and sector three generates 0.74 units of cycling per unit of its final outflow. So, to calculate the total amount of cycling:

$$TST_c = \mathbf{i}' \cdot \begin{pmatrix} 0.33 & 0 & 0 \\ 0 & 1.07 & 0 \\ 0 & 0 & 0.74 \end{pmatrix} \cdot \begin{pmatrix} 5 \\ 1 \\ 10 \end{pmatrix} = \mathbf{i}' \cdot \begin{pmatrix} 1.64 \\ 1.07 \\ 7.38 \end{pmatrix} = 10.08 \tag{4.7}$$

However, when decomposing the original table into its product-based structures and adding the amount of cycling generated by each of these, 27.56 units of cycling are found (see appendix B.1 for the different structures). This result is close to the overestimated amount of cycling that can be found by exploring the aggregated structure, which is

30 (it is the same amount of cycling as determined for table 4.1 since the inter-sectoral structure has not been modified) but it is distant from the total amount of cycling found using the method suggested in Finn (1976, pg. 373). Therefore, the total amount of cycling calculated with Finn's method is not reliable, even for systems with non-null final outputs.

For these three reasons, this research will build on the method developed in Ulanowicz (1983) to quantify the level of systemic cycling rather than the method developed in Finn (1976).

4.3 The product-based decomposition of the production structure

The *product-based decomposition* of the production structure reveals the different structures associated to the production of each final good. Each *product-based structure* entails the primary resources, intersectoral flows and emissions corresponding to the production of a specific final good — the good on which the decomposition is based.

4.3.1 Methodology to decompose the complete structure of the economic system into its product-based structures

Each product-based structure consists of the emissions[12], primary resources and intermediate production required to produce a specific final good p; thus, calculating such structure requires finding the emissions, primary resources and intermediate production required to produce p.

For ease of comparison and calculation, each product-based structure is calculated per unit of final good. This has the extra advantage that the whole product-based structure becomes an indicator set of the resource efficiency or intensity of the economic system since it represents the emissions, primary resources and intermediate production generated or consumed per unit of final good p. This is because each component of the product-based structure represents an intensity: the primary resources become the primary resource intensities (per unit of final good produced) and the emissions become the emission intensities (per unit of final good produced). Thus, inverting the sum of the resource intensities gathers the resource efficiency of the economic system to produce one unit of the good on which the product-based structure is based.

[12]The product-based decomposition can also be applied to monetary IOTs, i.e. without emissions. Also, following the same logic, the resource-based decomposition can be developed, finding the structure associated to a given primary input, by using an input-driven model.

First, it is shown how to calculate each component of the product-based structure and, then, it is shown how to re-aggregate them as the original PIOT.

4.3.1.1 The product-based decomposition of a PIOT

Recalling chapter 3, PIOTs require a specific type of output-driven model able to endogenise the disposals to nature and calculate the primary resources and emissions associated to a specific final demand. Only the method developed by Xu and Zhang (2009) and the second method suggested in Suh (2004a) are able to do that and can hence be used to calculate the decomposition suggested below. Here, the decomposition is performed using the model developed by Xu and Zhang (2009) because the resulting physical structures, i.e. the technical coefficients and Leontief inverse matrices, already correspond to the *complete physical structure* of the economic system, whereas the structure revealed by the second method suggested in Suh (2004a) is only a partial representation of the physical structure (c.f. section 3.2.4.1).

The main difference between the model developed by Xu and Zhang (2009) and traditional output-driven models is that emissions — which are generated by the production structure since they are produced simultaneously with the intermediate and final goods — are endogenised in the Leontief inverse $\underline{\mathbf{L}}$. The notation from chapter 3 is used: $\mathbf{E}$ is the emission matrix defined as $\mathbf{E} = \hat{\mathbf{w}} \cdot \hat{\underline{\mathbf{x}}}^{-1}$ and the technical coefficient matrix is defined as $\underline{\mathbf{A}} = \mathbf{Z} \cdot \hat{\underline{\mathbf{x}}}^{-1}$, then $\underline{\mathbf{L}} = (\mathbf{I} - \underline{\mathbf{A}} - \mathbf{E})^{-1}$.

To identify the primary resources, emissions and intersectoral components of a specific product-based structure, let a prepended superscript s_p denote the p-based structure association of each component. Finally, to emphasise the unitary final demand, let ${}^{s_p}\mathbf{u}$ be the unity vector representing one unit of final good p instead of using ${}^{s_p}\mathbf{f}$.

The total outputs associated to the production of one unit of p are

$$ {}^{s_p}\underline{\mathbf{x}} = \underline{\mathbf{L}} \cdot {}^{s_p}\mathbf{u} \tag{4.8} $$

Then, all components of the product-based structure of product p can be calculated as follows (recalling that primary resource input coefficients are $\mathbf{c}^r = \mathbf{r}' \cdot \hat{\underline{\mathbf{x}}}^{-1}$),

$$ {}^{s_p}\mathbf{w} = \mathbf{E} \cdot {}^{s_p}\underline{\mathbf{x}} \tag{4.9} $$

$$ {}^{s_p}\mathbf{r} = \mathbf{c}^r \cdot {}^{s_p}\underline{\mathbf{x}} \tag{4.10} $$

$$ {}^{s_p}\mathbf{Z} = \underline{\mathbf{A}} \cdot {}^{s_p}\underline{\mathbf{x}} \tag{4.11} $$

Thus, the linear decomposition of a PIOT with n sectors gathers n different product-based structures (portrayed in table 4.8), each revealing the production structure of the good analysed.

Also, the product-based structures can be interpreted as the systemic life-cycle assessment of producing a given final good since each product-based structure reveals the resources and emissions generated by the whole system to produce one unit of the final product. In this sense, the product-based structures constitute a different approach to calculate the Material Input per Service unit (MIPS), usually requiring tedious LCA studies (Ritthoff et al., 2002).

	Sec. 1 ... Sec. n	fd	emissions	Tot. outputs
Sector 1				
$\vdots$	${}^{s_p}\mathbf{Z}$	${}^{s_p}\mathbf{u}$	${}^{s_p}\mathbf{w}$	${}^{s_p}\underline{\mathbf{x}}$
Sector n				
Primary resources	${}^{s_p}\mathbf{r}'$			
Total inputs	${}^{s_p}\underline{\mathbf{x}}'$			

TABLE 4.8: Components of a product-based structure or product-based IOT.

4.3.1.2 Relationship between the product-based structures and the original structure

Below, it is demonstrated that the original PIOT is a linear combination of its product-based structures.

The final demand $\mathbf{f}$ is a linear combination of the product-based final demands, as follows

$$\mathbf{f} = \sum_{p=1}^{n} f_p \cdot {}^{s_p}\mathbf{u} \tag{4.12}$$

Using the commutative property of addition, the total outputs of the whole economy $\underline{\mathbf{x}}$ are related to the total outputs of each product-based structure ${}^{s_p}\underline{\mathbf{x}}$ proportionally to the final goods produced by each product-based structure f_p, as follows:

$$\begin{aligned}
\underline{\mathbf{x}} &= \underline{\mathbf{L}} \cdot \mathbf{f} \\
&= \underline{\mathbf{L}} \cdot \sum_{p=1}^{n} f_p \cdot {}^{s_p}\mathbf{u} \\
&= \sum_{p=1}^{n} f_p \cdot \underline{\mathbf{L}} \cdot {}^{s_p}\mathbf{u} \\
&= \sum_{p=1}^{n} f_p \cdot {}^{s_p}\underline{\mathbf{x}} \qquad (4.13)
\end{aligned}$$

Equations 4.9, 4.10, and 4.11 relate ${}^{s_p}\mathbf{w}$, ${}^{s_p}\mathbf{r}$ and ${}^{s_p}\mathbf{Z}$ to ${}^{s_p}\underline{\mathbf{x}}$; thus, using equation 4.13 in equations 4.9, 4.10 and 4.11, $\mathbf{r}$, $\mathbf{Z}$, $\mathbf{f}$ and $\mathbf{w}$ can be related to their corresponding product-based counterparts ($\mathbf{f}$ being a trivial case seen in equation 4.8), as follows:

$$\mathbf{Z} = \underline{\mathbf{A}} \cdot \underline{\mathbf{x}} = \underline{\mathbf{A}} \cdot \sum_{p=1}^{n} f_p \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot \underline{\mathbf{A}} \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot {}^{s_p}\mathbf{Z} \qquad (4.14)$$

$$\mathbf{w} = \mathbf{E} \cdot \underline{\mathbf{x}} = \mathbf{E} \cdot \sum_{p=1}^{n} f_p \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot \mathbf{E} \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot {}^{s_p}\mathbf{w} \qquad (4.15)$$

$$\mathbf{r} = \hat{\mathbf{c}}^r \cdot \underline{\mathbf{x}} = \hat{\mathbf{c}}^r \cdot \sum_{p=1}^{n} f_p \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot \hat{\mathbf{c}}^r \cdot {}^{s_p}\underline{\mathbf{x}} = \sum_{p=1}^{n} f_p \cdot {}^{s_p}\mathbf{r} \qquad (4.16)$$

Since every component of the complete structure of the economic system — $\mathbf{r}$, $\mathbf{Z}$, $\mathbf{f}$ and $\mathbf{w}$ — is linearly related to their corresponding product-based counterpart (${}^{s_p}\mathbf{r}$, ${}^{s_p}\mathbf{Z}$, ${}^{s_p}\mathbf{f}$ and ${}^{s_p}\mathbf{w}$), the complete structure of the economic system (${}^{agg}IOT$) can be re-aggregated, since it is linearly related to each product-based structure (${}^{s_p}IOT$) by multiplying each product-based structure by the final demand of the final good produced by each structure f_p, as follows

$${}^{agg}IOT = \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT \qquad (4.17)$$

where

$${}^{agg}IOT = \left(\begin{array}{c|c|c} {}^{agg}\mathbf{Z} & {}^{agg}\mathbf{f} & {}^{agg}\mathbf{w} \\ \hline {}^{agg}\mathbf{r}' & & \end{array} \right) \qquad (4.18)$$

and

$${}^{s_p}IOT = \left(\begin{array}{c|c|c} {}^{s_p}\mathbf{Z} & {}^{s_p}\mathbf{f} & {}^{s_p}\mathbf{w} \\ \hline {}^{s_p}\mathbf{r}' & & \end{array} \right) \qquad (4.19)$$

Equation 4.17 constitutes a key analytical tool because it implies that the properties of the original structure are linearly related to the properties of each product-based structure. So, for instance, it is possible to find the emissions of each product-based structure and re-aggregate them to find the emissions of the original structure. In this sense, each product-based structure can be scaled to its actual level of activity, to assess its absolute contribution to the original structure. The actual contribution of each product-based structure can be found by multiplying each product-based structure by the amount of final goods it produces, as follows:

$$^{s_p,\ actual}IOT = f_p \cdot {}^{s_p}IOT \tag{4.20}$$

4.3.2 Numerical example

Using the equations suggested in this section, the product-based structures of the three sector PIOT presented in section 3.2.2.3 are calculated and displayed below: the product-based structure for agricultural goods in table 4.9, the one for manufacturing goods in table 4.10 and the one for service goods in table 4.11.

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.73	0.10	0.04	1	2.26	4.12
Man.	0.31	0.44	0.10	0	0.34	1.19
Ser.	0.16	0.01	0.01	0	0.13	0.31
$\mathbf{r}'$	2.93	0.64	0.16			
$\underline{\mathbf{x}}'$	4.12	1.19	0.31			

Table 4.9: Product-based structure for agricultural final goods [in million tons]

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.18	0.26	0.01	0	0.57	1.03
Man.	0.07	1.19	0.04	1	0.94	3.25
Ser.	0.03	0.04	0.00	0	0.06	0.14
$\mathbf{r}'$	0.73	1.75	0.07			
$\underline{\mathbf{x}}'$	1.03	3.25	0.14			

Table 4.10: Product-based structure for manufacturing final goods [in million tons]

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.27	0.17	0.25	0	0.85	1.55
Man.	0.11	0.78	0.62	0	0.61	2.14
Ser.	0.05	0.02	0.08	1	0.81	1.98
$\mathbf{r}'$	1.10	1.15	1.02			
$\underline{\mathbf{x}}'$	1.55	2.14	1.98			

Table 4.11: Product-based structure for service final goods [in million tons]

Using equation 4.20, the actual contribution of each product-based structure is found, i.e. each product-based structure is scaled to its total contribution to the actual, aggregate structure. The actual contribution of the agricultural, manufacturing and services product-based structures are represented in tables 4.12, 4.13 and 4.14 correspondingly.

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	14.51	1.96	0.8	20	45.23	82.49
Man.	6.26	8.71	1.97	0	6.87	23.81
Ser.	3.13	0.3	0.27	0	2.58	6.27
$\mathbf{r}'$	58.59	12.84	3.24			
$\underline{\mathbf{x}}'$	82.49	23.81	6.27			

Table 4.12: Actual contribution of the agricultural product-based structure [in million tons]

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	120.17	176.22	12.28	0	374.66	683.33
Man.	51.84	783.73	30.3	658	618.64	2142.5
Ser.	25.92	26.9	4.09	0	39.71	96.63
$\mathbf{r}'$	485.4	1155.65	49.95			
$\underline{\mathbf{x}}'$	683.33	2142.5	96.63			

Table 4.13: Actual contribution of the manufacturing product-based structure [in million tons]

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	18.32	11.82	16.92	0	57.12	104.18
Man.	7.9	52.56	41.74	0	41.49	143.69
Ser.	3.95	1.8	5.64	67	54.71	133.1
$\mathbf{r}'$	74	77.51	68.81			
$\underline{\mathbf{x}}'$	104.18	143.69	133.1			

Table 4.14: Actual contribution of the services product-based structure [in million tons]

4.4 Finding the resources and emissions associated to cycling

Before being able to calculate the complete cyclic structure, the amount of resources and emissions generated by cycling itself need to be quantified. This section aims to find a method to quantify these flows since previous methods characterising systemic cycling or developing cycling metrics did not characterise nor calculate them (see section 2.6).

4.4.1 The case of a simple cycle

Given a sector with a resource input of a, a self-cycle[13] of b — the only cycle going through the sector in this example — , a useful output of g (e.g. manufactured goods) and a useless output of e (e.g. emissions), the resource efficiency of the sector is defined as[14]

$$\eta = \frac{b+g}{a+b} \tag{4.21}$$

Since b goes through the compartment, it incurs $b \cdot (1-\eta)$ of emissions — i.e. cycling losses. However, these cycling losses need to be compensated with part of the input a to keep the cycling flow constant since it is assumed that the system is stationary (as in input-output analysis). So, the input a can be decomposed between the acyclic flow s and a cycle-feeding flow c^f. Since there have been $b \cdot (1-\eta)$ cycling losses, an equivalent feeding flow $c^{f'}$ is derived from the input a to compensate the cycling losses.

However, this new feeding flow $c^{f'}$ will in turn flow through the compartment and incur further losses equivalent to $c^{f'} \cdot (1-\eta) = b \cdot (1-\eta) \cdot (1-\eta)$. Again those losses need to be compensated and a new feeding flow equal to the losses which is again derived from the input, incurring again new losses and so on infinitely. Thus, both the cycle-feeding flows r^c and cycling losses w^c can be represented by the same following power series:

$$\begin{aligned} w^c = r^c &= b \cdot (1-\eta) + b \cdot (1-\eta) \cdot (1-\eta) + b \cdot (1-\eta) \cdot (1-\eta) \cdot (1-\eta) + \dots \\ w^c = r^c &= b \cdot (1-\eta) \cdot [1 + (1-\eta) + (1-\eta)^2 + \dots] \end{aligned} \tag{4.22}$$

It is known that $1 + a + a^2 + a^3 + \cdots = (1-a)^{-1}$, for $|a| < 1$, the same power series behind the Leontief inverse (Miller and Blair, 2009). Since the systemic resource efficiency also ranges from 0 to 1, this power series can be applied to the case under study. Thus,

$$w^c = r^c = b \cdot (1-\eta) \cdot [1 - (1-\eta)]^{-1} = \frac{b \cdot (1-\eta)}{\eta}, \; for \; \eta \; \in]0, 1[\tag{4.23}$$

In appendix A, a different analytical demonstration corroborates expression 4.23.

Thus, the same level of cycling can generate different levels of *cycling losses* and require a different amount of *cycle-feeding* flows depending on the resource efficiency of each sector. This implies that even the same cycle will induce different sectoral levels of emissions if the different sectors involved in the cyclic path have different sectoral resource efficiencies.

[13] The self-cycle can also be considered a simple cycle coming and going to another compartment, the important feature is that the cycle inflow equals the cycle outflow.

[14] This definition of sectoral resource efficiency is equivalent to the one provided in equation 4.54. Only the latter follows the notation of input-output tables.

4.4.2 Using the *cycling throughput* to calculate the resources and emissions due to different cycles through a given sector

The previous section calculated the *cycle-feeding flows* and *cycling losses* of a sector with a single cycling flow; however, a sector can be linked to several cycles simultaneously. What would be the *cycle-feeding flows* and *cycling losses* in this case? In this section, the *cycling throughput* concept is used to answer this question.

From a sector's "perspective", it is irrelevant whether the cycles passing through it are self-cycles, part of a short cycle or part of a long cycle. As demonstrated in equation 4.23, the *cycle-feeding flows* and *cycling losses* only depend on the sectoral efficiency and the value of the cycling flow to be maintained. Thus, the *cycle-feeding flows* and *cycling losses* are independent of how long the cycle is; they depend solely on the size of the flow to be maintained through the specific sector and the sector's resource efficiency.

Since the path of the cycles is irrelevant for the sector, only the level of cycling is important, and thus all cycles going through a compartment can be aggregated as the sectoral *cycling throughput* which, together with the sectoral efficiency, will determine the total *cycle-feeding flows* and *cycling losses* of that sector. Thus, the *cycling throughput* is a powerful analytical concept since it enables to calculate all *cycle-feeding flows* and *cycling losses* of all cycling flows going through a given sector at once.

The *cycling throughput* of sector i is noted c_i and also represents the degree of linkage of a specific sector with the rest of the sectors in terms of cycling exchanges.

Since by definition, cycle inputs equal cycle outputs, the *cycling throughput* of all sectors can be calculated from $\mathbf{Z}^c$ (i.e. the intersectoral component of cycling[15]), either as its row or column sum:

$$\mathbf{c} = \mathbf{Z}^c \cdot \mathbf{i} = \left(\mathbf{i}' \cdot \mathbf{Z}^c\right)' \tag{4.24}$$

Using the *cycling throughput* concept to calculate the emissions and primary resources due to *all* cycles going through sector i, equation 4.23 becomes

$$w_i^c = r_i^c = \frac{c_i \cdot (1 - \eta_i)}{\eta_i} \tag{4.25}$$

[15] $\mathbf{Z}^c$ has been previously defined in equation 2.41 according to the definition of Ulanowicz (1983). However, the $\mathbf{Z}^c$ will be redefined in equation 4.27 (section 4.5.1) because the original definition in Ulanowicz (1983) did not consider part of the structure.

4.4.3 Exploring the systemic effects of cycling on resource consumption and emission generation

Equation 4.25 implies that maintaining cyclic flows is more resource efficient regarding the primary resources required by the system than generating the same amount in an acyclic manner. Consider two sectors with the same resource efficiency and producing one unit of useful output ($f = 1$ in the case of acyclic flows and $c = 1$ in the case of cyclic flows). Equation 4.25 implies that maintaining one unit of cycled useful output requires $\frac{1-\eta}{\eta}$ units of primary resources and generates the same amount of emissions. The efficiency rules of acyclic flows imply that to maintain one unit of useful output, $1/\eta$ units of resources are required and $\frac{1-\eta}{\eta}$ units of emissions are generated (c.f. figure 4.3).

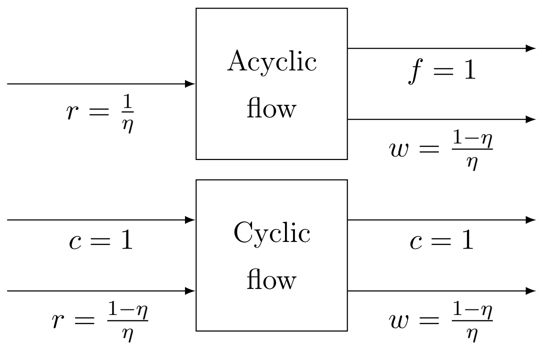

FIGURE 4.3: Resources and emissions associated to maintaining a unit of an acyclic and a cyclic flows

Thus, the primary resources required to maintain one unit of acyclic useful output are always higher than the primary resources required to maintain one unit of cyclic useful output, as equation 4.26 demonstrates.

$$\frac{1-\eta}{\eta} < \frac{1}{\eta} \ , \ \forall \eta \ \epsilon \ ]0,1[\tag{4.26}$$

The primary resources required per unit of acyclic and cyclic useful output are plotted in figure 4.4. The difference between the resources required for both types of flows tends to zero when the efficiency tends to zero and tends to one when the efficiency tends to one. In other words, the primary resource "savings" (or advantage) of cycling compared to acyclic flows tends to zero when the sectoral efficiency tends to zero and is maximal when the sectoral resource efficiency equals one — i.e. when the cycle would be virtually maintained without requiring any primary resource input.

This result is crucial to understand the metabolism of dissipative systems because the reasoning can be extended from the sector level to system level. Suppose a system is composed by n sectors, if each sectors aims to produce one unit of useful output, the

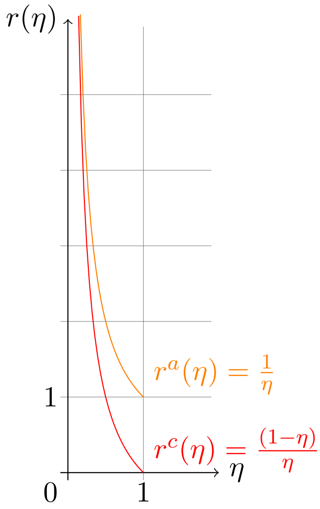

FIGURE 4.4: Primary resources required to maintain one unit of cyclic flow (r^c) and one unit of acyclic flow (r^a) as a function of the sectoral efficiency, for $\eta \in]0,1[$.

whole system will require $3 \cdot \frac{1-\eta}{\eta}$ units of primary resources by producing them in a cyclic manner and $3 \cdot \frac{1}{\eta}$ in the acyclic case; thus equation 4.26 is still valid at system level. So, from a system perspective, it is cheaper in terms of primary resources to produce and maintain cyclic flows *within* the system than to produce acyclic flows which ultimately *leave* the system. Thus, systems aiming to maintain a given internal throughput at the lowest primary resource cost shall aim to increase their internal cycling for it requires less resources.

However, while cycling reduces the primary resource requirements to maintain a given system throughput, it reduces the system-wide efficiency when considering the (final) outputs through the system. Cycling flows might be necessary but, by definition, they are not embedded in the final output; thus, in addition to the cyclic flows, there must be a certain amount of acyclic flows which do generate the final output. So, since the cyclic flows use resources on top of the resources required to create the final output, they lower the resource efficiency of the overall system vis-à-vis the final outputs of the system in all cases. In other words, while cycling maximises the system throughput (of which cycling plays a major role), it increases the resources requirements in order to produce final outputs. Thus, systems aiming to maintain a given final output at the lowest resource cost shall aim to reduce their internal cycling for it requires resources that do not contribute to the final output.

Thus, the key idea is that the systemic effects of cycling depend on which is the "reference" flow to be maximised: either internal flows — corresponding to intersectoral cycling in a PIOT — or external outflows — corresponding to products for final consumption in a PIOT.

For completeness, a generic formulation of the resources and emissions associated to an acyclic and a cyclic process are presented in figure 4.5.

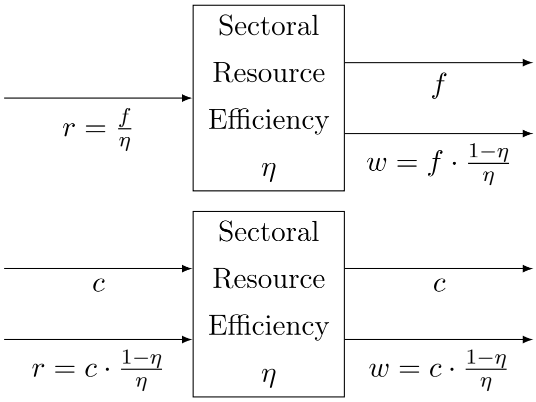

FIGURE 4.5: Generic resources (r) and emissions (w) associated to an acyclic (f) and a cyclic (c) flow

4.4.4 On pre-consumer and post-consumer cycling

The findings of the previous section have key implications in the theoretical understanding of cycling, since they imply that different types of cycling might have opposing effects regarding the resource efficiency of the system. In particular, while some types of cycling might lower the resource efficiency of the overall system (as suggested in the previous section), other types might increase it, as suggested by the mainstream literature studying industrial systems (c.f. section 2.5.1).

So, the concept of cycling is tightly linked to the concept of resource efficiency, since different types and degrees of cycling affect differently the resource efficiency of the overall system. However, the concept of resource efficiency must be refined since two types of resource efficiency exist, affecting the system performance differently: the *sectoral resource efficiency* which determines the efficiency of each sector in transforming a given resource into goods and emissions; and the *economy-wide resource efficiency*, which determines the efficiency of the overall economic system in transforming a given set of resources into final goods. The *economy-wide resource efficiency* will be later called *macroscopic resource efficiency* since it reveals the macroscopic properties of the economic system, and *sectoral resource efficiencies* will be called *mesoscopic resource efficiencies* since they reveal the properties of the sub-components of the economic system. So, the macroscopic resource efficiency is determined by how the different sectors are linked between each other (i.e. the level and type of cycling) and by the different mesoscopic resource efficiencies. The analytical determination of these relationships will be developed in chapter 5, after the cyclic structure has been analytically determined in section 4.5.

The key to identify each type of cycling is to focus on the "reference" flows that should be maximised vis-à-vis the resources used by the system. The main aim of the economic system is to produce goods and services for final consumption. Thus, according to the findings of the previous section, cycling involving final goods and services would improve the resource efficiency of the economic system. This type of cycling is hereafter called *post-consumer cycling* because it implies (re)cycling goods that have been previously consumed by the final demand sectors, of which the consumer sector is the driving force. This finding is aligned with the literature about (re)cycling (Ayres, 1996; Graedel et al., 2011; UNEP, 2011b) and its empirical LCA studies (WRAP, 2010).

Below, several cycling structures representing the different cycling cases identified in the previous section are presented to provide more concrete, quantifiable examples.

In figure 4.6, it is exemplified how post-consumer cycling affects the macroscopic resource efficiency of the economic system. Two cases of systems transforming and using a specific material are provided, e.g. aluminium used in aluminium cans. The flow to be maximised vis-à-vis the resources used by the system is the flow used by the household sector, fixed in 1000 tons (e.g. of aluminium or equivalent amount of aluminium cans). The two cases are constituted by the productive system and the household sector. The hypothetical physical structure at the top of the figure assumes that 60% of used goods are (re)cycled into the productive system. The figure at the bottom assumes that all goods are disposed of after consumption in an acyclic manner (e.g. landfilled). The system with post-consumer recycling has a macroscopic resource efficiency of $\frac{1000}{500} \cdot 100 = 200\%$ while the system without recycling has a macroscopic efficiency of $\frac{1000}{1100} \cdot 100 = 90\%$. This result confirms that *post-consumer* cycling increases the macroscopic resource efficiency, even above 100%[16], because final goods are being produced with used goods, producing more goods than resources extracted. In this case, cycling is "beneficial" because it helps maximising the internal throughput of produced goods for household consumption at a lower resource cost than acyclic flows. Thus, in the case of post-consumer cycling, a cyclic physical structure is more resource efficient than an acyclic one.

However, cycling itself consumes resources (c.f. section 4.4.2), so it lowers the resource efficiency of the system when affecting material paths not involved in the material flow to

[16]Efficiencies over 100% are possible, especially in cyclic processes, because few resources or energy are required to maintain the cyclic flow. Since only a little amount of resource is used to mobilise or transform the matter or energy, the ratio exceeds 100%. In thermodynamics, heat pumps are a typical case of processes with efficiencies over 100%, since little energy is used compared to the energy displaced, which is the "reference" flow.

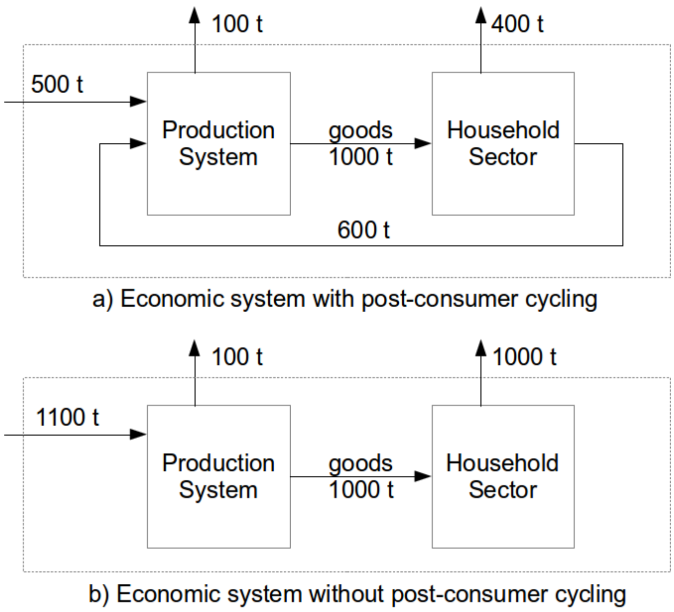

FIGURE 4.6: Hypothetical representation of the physical structure of the production–consumption system with and without post-consumer cycling

be maximised vis-à-vis resource consumption. This type of cycling is called *pre-consumer cycling* because it mostly happens *before* the final consumption stage of goods[17].

In figure 4.7, it is exemplified how pre-consumer cycling affects the macroscopic resource efficiency of the economic system. Three cases of systems transforming and using a specific material are provided, e.g. iron used to produce a car. The three cases represent the productive system only (excludes the household consumption sector), so the usable output of the system is the final good that will be consumed/used by the household sector. In the three cases, the same system output is produced (e.g. 900 kg of iron, corresponding to the weight of a car). Two sectors are present: the car manufacturing sector and the iron smelting sector, which receives iron ore and can recycle the iron wasted during car production. The first two cases assume that the car manufacturing sector has a sectoral resource efficiency of 90%, i.e. 90% of the iron input is embedded in the final output. In the first case, the wasted iron is fully recycled by the smelting sector; in the second case, the wasted iron is landfilled. The third case assumes that the car manufacturing sector manages to embed all iron into the final product, implying a resource efficiency of 100%. While this cannot always be possible, this extreme example aims to demonstrate that, in the case of pre-consumer cycling, an acyclic structure (based on minimisation of material use during production) is preferable to a cyclic structure

[17]Strictly speaking, pre-consumer cycling represents all cycling happening within the economic system excluding the cycling involving final goods for final consumption, so it might be possible that some degree of pre-consumer cycling exists “after” final consumption, e.g. between waste management and recycling industries.

(based on recycling of waste materials). The macroscopic resource efficiencies of the three systems are, correspondingly:

a) $\frac{900}{1000} \cdot 100 = 90\%$
b) $\frac{900}{1100} \cdot 100 = 81.8\%$
c) $\frac{900}{990} \cdot 100 = 91\%$

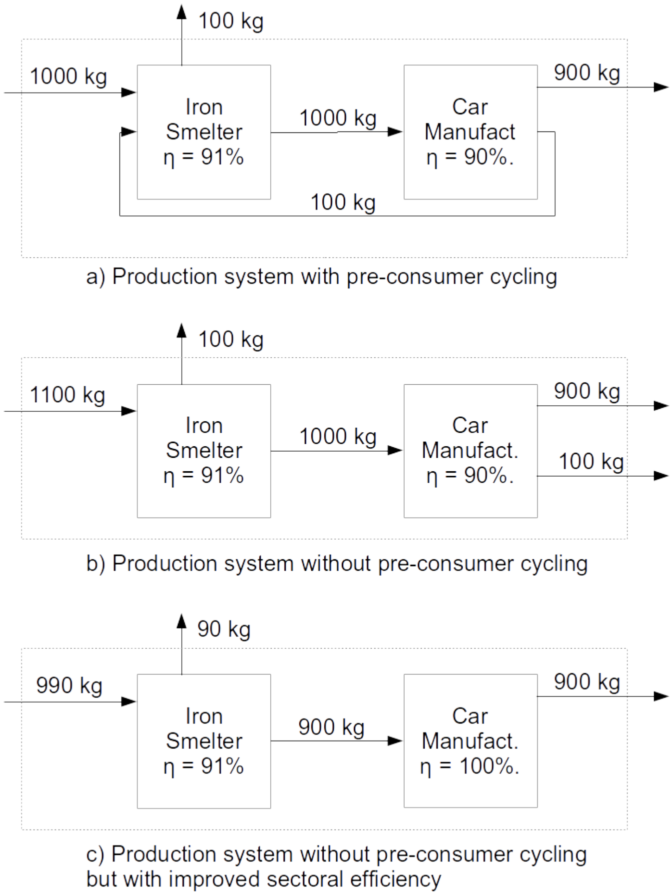

FIGURE 4.7: Hypothetical representation of the physical structure of the production system with and without pre-consumer cycling and with improved sectoral resource efficiency.

The difference in macroscopic resource efficiency between the first and the second case suggests that it is preferable that pre-consumer cycling exists given a fixed set of sectoral resource efficiencies. However, the difference in macroscopic resource efficiency between the first and third case suggests that it is preferable that a more efficient acyclic process substitutes pre-consumer cycling. This latter case does not apply to post-consumer cycling since an acyclic flow after consumption implies that the materials are disposed out of the system, lowering systematically the macroscopic resource efficiency of the system.

The difference in macroscopic resource efficiencies between the first and third case is apparently low. However, only a single material flow has been assessed, so it is expected that this difference would increase as other factors are included in the analysis (e.g. the transportation required to bring the wasted iron to the smelting sector or the energy required to melt the iron, since in the first case, the smelting sector has a throughput of 1100 kg while only 990 kg in the third case, requiring less energy). Thus, in the case of pre-consumer cycling, a more efficient acyclic physical structure is preferable to a cyclic structure from a macroscopic resource efficiency perspective. In other words, pre-consumer cycling should be minimised in favour of more resource efficient acyclic processes, as previously stated in Bailey et al. (2004b) albeit without any formal demonstration supporting the statement.

This differentiation between cycling flows within the economic system is similar to the one suggested in Bailey et al. (2004b), where cycling is divided between cycling occurring within the production system and cycling going to the consumption sector. These are characterised using two cycling metrics called "production" and "consumption cycling efficiencies" (Bailey, 2000; Bailey et al., 2004b), which do not necessarily provide an accurate measure since the metric is related to TST_c (see section 2.6.3.2), which has been proven to be a misleading measure (see section 4.2.3) and their structure is not formally compared as done in the previous section nor the different system components were related amongst them. It is important to note that previous section relates the emission generation to the level of cycling going through the sector and its resource efficiency.

Before developing a method to identify the cyclic structure within a physical input-output table, some theoretical aspects on the aggregation of material flows are discussed below.

4.4.5 On trans-cycling and re-cycling

The cyclic flows can either be constituted by *trans-cycling* or *re-cycling* flows. *Re-cycling* refers to the cycling of a given material to be re-used as raw material: e.g. the copper cable fabrication sector sends the copper debris back to the smelting sector, which produces copper cathode, which can be used again as raw material to fabricate copper cables. *Trans-cycling* is a new term coined to describe:

- cyclic flows of a given material not re-used as raw material, i.e. exchanged as finished (intermediate) goods. E.g., figure 4.8-a represents the flows of wood through the forestry and manufacturing sectors. The forestry sector sells 20 tons of wood to the manufacturing sector to produce tools, the manufacturing sector sells tools containing 10 tons of wood out of the productive system (e.g. to the household sector) and sells tools containing 5 tons of wood back to the forestry sector; 5 tons of wood are disposed of out of the entire system. This creates a *transcycle* of 5 tons of wood between the manufacturing and forestry sector.

- cyclic flows of different materials between sectors: e.g., figure 4.8-b represents the flows of iron through the manufacturing and forestry sectors: the manufacturing extracts 100 tons of iron which are transformed in tools, part of which embed 65 tons of iron and are sold outside the productive system (e.g. to the household sector) and part of the tools are sold to the forestry sector, containing 15 tons of iron. No cycle is constituted by iron flows alone. However, when the material flows of iron and wood are aggregated, as in figure 4.8-c, a new transcycle of 20 tons appear between the manufacturing and forestry sectors: 5 tons of which are due to trans-cycling of a given material (as seen in figure 4.8-a), and 15 tons are due to the exchange of different materials (wood and iron).

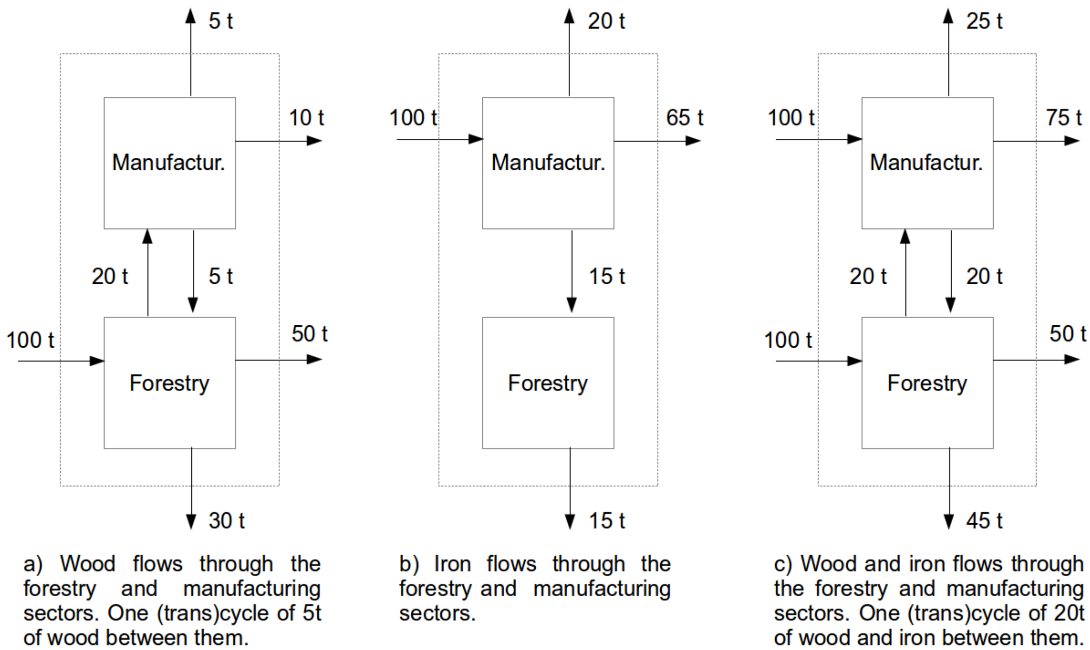

FIGURE 4.8: Three hypothetical representations of the physical structure of the production system for different cases and aggregation levels of transcycling.

The rationale behind merging two types of material flows to constitute a cycle (e.g. cyclic exchange of wood and metallic tools) lays on the idea that the productive process requires cyclic exchanges to maintain its activity. E.g., the metallic tools are not embedded in the final product of the forestry sector nor necessarily the wood is embedded in the final products of the manufacturing sector (e.g. used for energy or internal purposes), so in both cases the material is exchanged in a cyclic manner but not embedded in final production. Thus, such cyclic interactions between sectors are required to maintain its level of activity: the forestry sector cannot operate without the metallic tools and the manufacturing sector cannot operate without wood, and this requirement is reflected in each sectoral resource efficiency. The idea that the cyclic structure corresponds to the maintenance structure of the economic system is developed below, in section 4.5.1.

Such aspect of cycling has not been considered in previous literature, which has traditionally assessed the recycling of specific material flows (Spatari et al., 2002; Müller et al., 2006; Graedel et al., 2011; Chen and Graedel, 2012). Also, the reviews of cycling metrics did not identify this aspect of cycling (Suh, 2005; Bailey et al., 2008).

Also, post-consumer trans-cycling exists but it is not characterised by a complete cyclic path of the material flow. In this case, the material flows are re-introduced in the productive system as raw materials but in a different sector than the one through which they originally entered the economic system. Thus, no closed (simple) cycle is formed; instead, the shape of the structure resembles an "S", as depicted in figure 4.9: e.g. silicon is extracted to produce a glass bottle, the bottle is recycled after consumer use, re-introduced in the cement industry to produce cement, which stays within the economic system as part of the stock-in-use (e.g. a building). So, post-consumer trans-cycling refers to post-consumer re-cycling that does not create a cyclic path.

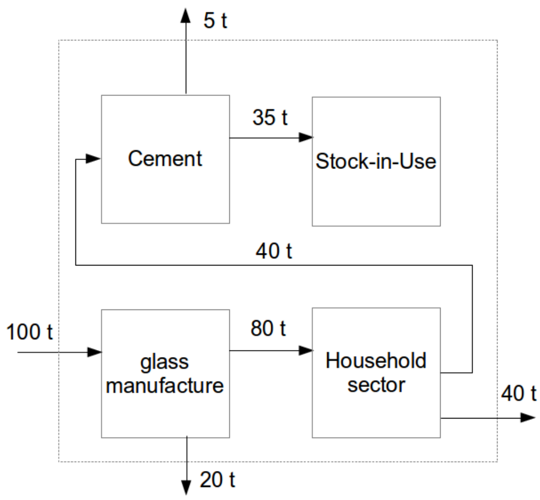

Figure 4.9: Hypothetical representations of post-consumer trans-cycling.

Re-cycling also happens at pre-consumer and post-consumer level. A re-cycling pre-consumer example with copper was provided at the beginning of the first paragraph of this section. A re-cycling post-consumer example is the material flows that are re-cycled after consumption to be re-used as the same material (e.g. aluminium cans recycled after household consumption, c.f. figure 4.6).

Hereafter, *trans-cycling* and *re-cycling* are not differentiated from each other since the type of cycling does not affect the properties of cycling. When a trans-cycle of a given value exists, e.g. as in figure 4.8-c between the forestry and manufacturing sectors, the cycling flow is maintained according to the efficiency rules of each sector (c.f. equation 4.25), i.e. the forestry sector needs to extract primary resources (wood) and process it at its efficiency rate and the same applies to the manufacturing sector. This means that the theoretical representation and calculation of cycling developed in the previous and following sections apply to both trans-cycling and re-cycling.

Traditional PIOTs representing a single material can only characterise pre-consumer *re-cycling* and *trans-cycling* of a single material, since they only represent the intersectoral exchanges of a given material within the productive system. So, in order to characterise all *trans-cycling*, it is required that the PIOT represents aggregated material flows, in which case pre-consumer trans-cycling and re-cycling are represented simultaneously. In fact, the cycles identified within a PIOT aggregating several materials cannot be allocated to either trans-cycling nor re-cycling. To disaggregate trans-cycling from re-cycling, the PIOT would need to be disaggregated into a different PIOT for each material; the cycles happening within these PIOTs would be re-cycling and trans-cycling from a single material, and the difference between the total cycling flows and the cycling flows of the aggregate PIOT would correspond to trans-cycling of different materials.

Since the aim of this research is to characterise the total systemic effects of pre-consumer cycling, the illustrative example developed in chapter 6 will focus on a PIOT representing aggregated material flows. In this way, the cyclic structure that will be revealed will correspond to the total amount of cycling, i.e. trans-cycling and re-cycling. Next section shows how to identify the cyclic structure of cycling (and other structural components).

4.5 The cyclic–acyclic and direct–indirect sub-structures of the economic system

This section constitutes a key theoretical advancement of this thesis since it develops a method to identify the complete cyclic structure of a dissipative system such as the physical structure of the economic system. Also, the acyclic, direct and indirect structures are identified. Their function for the system is discussed. This method is based on the input-output framework and enables researchers to identify any type of cycling, i.e. pre-consumer and post-consumer cycling; in section 4.6.3 it is explained how to discriminate between the two types of cycling.

The traditional IO framework (Leontief, 1941; Miller and Blair, 2009) represent stationary systems with no interacting stocks[18]; thus, in this context, the cyclic flows are constant, generating a constant flow of emissions — called *cycling losses* — and requiring a constant flow of resources to maintain the level of cycling — called *cycle-feeding resources*.

[18]In the traditional IO framework, the only stocks that are considered are inventory changes, which are considered as final demand and are used for balancing purposes (Miller and Blair, 2009). However, while it is possible to include stock formation within the IO framework by including derivatives in the IOTs (Bailey et al., 2004b), this would imply to develop a dynamic analysis, which would fall out of the scope defined in section 2.6.6, which restricts the current analysis to a static one.

Intuitively, part of the *cycle-feeding resources* can be provided *directly* by primary resources but another part can be provided *indirectly* through sectoral interactions, i.e. some primary resources are transformed by some sectors before being embedded in a cyclic flow. Thus, the cyclic component is actually composed of cyclic–direct and cyclic–indirect sub-components. Similarly, some primary resources are directly embedded in final goods while some need some intermediate processing before being embedded into final goods; thus, the acyclic component is actually composed of a acyclic–direct and an acyclic–indirect sub-components. Thus, not only a cyclic–acyclic structure exists but also an indirect–direct structure exists.

In section 4.5.1, the theoretical foundations of the cyclic–acyclic and direct–indirect structures is provided, including a discussion of their function and explaining how these structures are intertwined.

In section 4.5.2, the analytical decomposition of a dissipative structure between its cyclic–acyclic and direct–indirect sub-structures is developed using the different structures identified and the cycling throughput concepts (c.f. section 4.4.2).

4.5.1 The cyclic–acyclic and direct–indirect structures as two meta-structures

Hereafter, using the prefix *meta-* to mean "about (its own category)", the concept of *meta-structure* is defined as the structure of the structure. Following that definition, the product-based structures constitute a meta-structure of the original structure and also, as argued above, a PIOT can also be decomposed into its cyclic and acyclic meta-structures or between its direct and indirect meta-structures.

Below, the cyclic–acyclic meta-structure is discussed first, and then the direct–indirect. Then, the theoretical notation of these meta-structures is developed and it is shown how both meta-structures are intertwined, requiring identifying separately the cyclic–direct, cyclic-indirect, acyclic–direct and acyclic–indirect meta-structural subcomponents. Finally, it is shown how to re-aggregate the different meta-structural subcomponents into a meta-structure or into the original structure.

4.5.1.1 The cyclic–acyclic structures as the maintenance–productive meta-structure

The intersectoral cyclic flows ($\mathbf{Z}^c$) are the core of the cyclic structure. The primary resources required to feed these cyclic flows are called the *cycle-feeding resources* and the emissions generated by the same cyclic flows are called the *cycling losses* (c.f. section 4.4.1).

The intersectoral cyclic flows — i.e. the intermediate goods exchanged between sectors forming cycles — are *unproductive* but necessary. In other words, the intermediate cycling flows (and the corresponding cyclic structure) are required to maintain the system's productive capacity but are not productive on their own. They represent the supplies required for each sector to keep producing (e.g. food, tools, processed resources) and are provided as intermediate goods. For example, the cycle between the agricultural and manufacturing sector could entail wood sent to the manufacturing sector to produce tools which are retuned to the agricultural sector to continue wood extraction or other purposes. On the other hand, the acyclic structure represents the primary resources that cross the economic system and exit it as final goods together with the associated emissions. Thus, at pre-consumer level — i.e. considering the production structure alone —, the cyclic structure can be described as the *maintenance* structure and the acyclic structure as the *productive* structure.

The cyclic structure can be further sub-divided between a direct and an indirect component. The cycle-feeding resources can either be provided *directly* by primary resources or *indirectly*, by intermediate resources — i.e. intermediate production —, enabling cycling in sectors that do not extract primary resources themselves. The former type of flows can be called cyclic–direct and the latter cyclic–indirect. Thus, cyclic–indirect flows are key to enable cycling in sectors that do not use primary resources and would otherwise not be able to contribute to the cycling — *maintenance* — of the system.

Acyclic flows can directly transform primary resources into final goods or, alternatively, undergo different cascaded acyclic processes before being embedded into final goods. This implies that the acyclic structure can also be further sub-divided between a direct and an indirect component.

To summarise, the cyclic and acyclic structures of the cyclic–acyclic meta-structure represent correspondingly the *maintenance* and *productive* structures of the system. Each of these components is in turn composed by direct and indirect flows, whose function is explored below.

4.5.1.2 The direct–indirect structures as the invariant–re-allocative meta-structure

The previous section argued that both the cyclic and acyclic structures can be fed directly by primary resources and also indirectly through primary resources previously transformed in intermediate goods. Thus, a direct–indirect meta-structure also exists.

The direct structure represents the flows that are directly extracted from primary resources and used straight away to fulfil their acyclic or cyclic "function": i.e. either to be productive or to maintain the system's productive capacity. Direct flows do not re-allocate resources within the structure since, by definition, the resources used directly are the primary resource extracted by the sector itself (otherwise they would be indirect), and the emissions are released by the sector itself. Thus, the flows enter and exit the same sector and, there is no re-allocation of flows within the productive structure. In other words, the direct structure maintains the distribution of primary inputs respective to the final outputs.

The indirect structure also uses primary resources but the resources are not directly used to fulfil their acyclic or cyclic "function"; they are transformed in intermediate goods before being used to fulfil their function. The inter-sectoral matrix represents the intermediate exchanges between sectors, revealing how primary resources and intermediate goods are transformed into other intermediate goods. Part of the intermediate structure is composed of the cyclic flows and the remainder part of the intermediate structure constitute the available indirect flows that need to be allocated between the cyclic and acyclic structures, since both require indirect flows — either because they do not have access to primary resources or because they require goods of higher degree of fabrication. Thus, the remainder of the intersectoral matrix after extracting the cyclic flows is the core of the indirect structure since it represents the available indirect flows that can feed either the productive (acyclic) structure or the maintenance (cyclic) structure.

This finding implies that the decomposition suggested by Ulanowicz (1983) (recall equation 2.41), which decomposes the intersectoral matrix into a cyclic and acyclic components, is misleading. In fact, the remainder contains the indirect flows that feed both the cyclic and acyclic structure. Thus, equation 2.41 should read instead:

$$\mathbf{Z} = \mathbf{Z}^c + \mathbf{Z}^{ind} \tag{4.27}$$

Since $\mathbf{Z}^{ind}$ constitutes the cascaded use of intermediate goods, it characterises the re-allocation of primary resources happening within the productive structure. The re-allocation process implies that the primary resources are extracted by a given sector but the final outputs are allocated between different sectors (either as emissions, final goods or both). For example, sector 1 extracts primary resources, transforms them into good 1 (producing some emissions in sector 1) and passes its production to sector 2 which transforms it into product 2 (producing some emissions in sector 2) and passes it to product 3 which transforms it into a final product (producing some emissions in sector 3). In this case, all inputs were taken by sector 1, but sectors 1, 2 and 3 generated emissions and only sector 3 produced final goods. Although the mass balance for each sector holds, the sector's primary input intake does not equal the sector's final goods generation: thus, the inputs of the systems were re-allocated within the system and ended as final output in different sectors. However, the re-allocation is only partial since the sector at the beginning of the cascade generates emissions itself and those emissions stay in the same sector which extracted the primary resources. More precisely, the system's re-allocation degree depends strongly on the resource efficiency of the first sector but also on the number of sectors through which the material flows cascade and their respective efficiencies.

To summarise, the function of the indirect meta-structure is to bring resources to the sectors that cannot use primary resources directly, i.e. that require materials with a higher degree of fabrication. Hereafter, the indirect meta-structure is said to *re-allocate* resources amongst the different system components. Conversely, the direct structure does not re-allocate resources, and does not contribute to the intersectoral interactions, leaving the structural pattern invariant.

4.5.1.3 The four sub-structures of a dissipative metabolism

As noted previously, both the cyclic and acyclic structures entail direct and indirect flows. Thus, the cyclic–acyclic and direct–indirect meta-structures overlap each other and the original structure can be decomposed into four meta-structural subcomponents: the cyclic–indirect, cyclic–direct, acyclic–indirect and cyclic–direct structures, which can be re-aggregated into the cyclic-acyclic or direct-indirect meta-structures, as represented in table 4.15.

The aim of this section is to develop the theoretical notation of the two meta-structures (and their sub-components), and show that they overlap, creating in fact a set of four sub-structures that need to be calculated independently before being able to aggregate them back into the cyclic–acyclic or direct–indirect meta-structures. The method to calculate them will be developed in section 4.4.

	Cyclic	Acyclic
Indirect	Cyclic–indirect structure	Acyclic–indirect structure
Direct	Cyclic–direct structure	Acyclic–direct structure

TABLE 4.15: The overlap of the cyclic–acyclic and direct–indirect meta-structures.

Recalling equation 4.27, the indirect inter-sectoral flows $\mathbf{Z}^{ind}$ are found after finding the inter-sectoral cycling $\mathbf{Z}^{c}$.

As argued in the previous section, part of $\mathbf{Z}^{ind}$ is used to maintain $\mathbf{Z}^{c}$ indirectly and another part is ultimately embedded as final goods. The indirect flows used to maintain cycling (i.e. used by part of $\mathbf{Z}^{c}$) are noted $\mathbf{Z}^{ind,c}$. So, $\mathbf{Z}^{ind,c}$ entails flows that are fully and specifically used to feed cycling and thus require a supporting structure bringing those flows up to the sector consuming them. Thus, the remainder ($\mathbf{Z}^{ind} - \mathbf{Z}^{ind,c}$) does not exclusively belong to the acyclic structure because part of that remainder needs to carry (or "bring") the flows that are used to feed the cycles indirectly — i.e. $\mathbf{Z}^{ind,c}$. Since this remainder contains both cyclic–indirect and acyclic–indirect flows, it is denoted $\mathbf{Z}^{ind,ac}$ and

$$\mathbf{Z}^{ind} = \mathbf{Z}^{ind,c} + \mathbf{Z}^{ind,ac} \tag{4.28}$$

Finally, this remainder can be divided between the flows feeding $\mathbf{Z}^{ind,c}$, noted $\mathbf{Z}^{ind,ac,c}$, and the indirect flows that do not belong to the cyclic structure, noted $\mathbf{Z}^{ind,ac,a}$:

$$\mathbf{Z}^{ind,ac} = \mathbf{Z}^{ind,ac,a} + \mathbf{Z}^{ind,ac,c} \tag{4.29}$$

Part of the indirect structure helps maintaining part of the cyclic matrix $\mathbf{Z}^{c}$, but part of $\mathbf{Z}^{c}$ is maintained directly. Thus, $\mathbf{Z}^{c}$ can be decomposed into its direct and indirect components: $\mathbf{Z}^{c,dir}$ and $\mathbf{Z}^{c,ind}$, as follows:

$$\mathbf{Z}^{c} = \mathbf{Z}^{c,ind} + \mathbf{Z}^{c,dir} \tag{4.30}$$

The intersectoral flows corresponding to $\mathbf{Z}^{dir}$ are null by definition because if the primary resources are consumed directly, they are not represented in the inter-sectoral matrix. Thus, hereafter, $\mathbf{Z}^{a,dir} = \mathbf{0}_{n,n}$, where $\mathbf{0}_{n,n}$ denotes a $n \times n$ matrix of zeros.

These different inter-sectoral structures are summarised in table 4.16, classified according to which meta-structure they belong.

	Cyclic	Acyclic
Indirect	$\mathbf{Z}^{c,ind} + \mathbf{Z}^{ind,c} + \mathbf{Z}^{ind,ac,c}$	$\mathbf{Z}^{ind,ac,a}$
Direct	$\mathbf{Z}^{c,dir}$	$\mathbf{0}_{n,n}$

TABLE 4.16: The intersectoral components of the four sub-structures of a dissipative physical structure.

The complete structures associated to each of the inter-sectoral flows represented in table 4.16 are presented below. Each of the structures entails primary resources, inter-sectoral flows, final goods and emissions. These structures are first represented in a simplified notation using * as superscript because it will be useful later on to have a simplified, compact notation to illustrate the re-aggregation of these sub-structures. The *simplified* notation tables for each structure are:

- table 4.17 for the cyclic–indirect structure,
- table 4.19 for the acyclic–indirect structure,

- table 4.18 for the cyclic–direct structure, and
- table 4.20 for the acyclic–direct structure.

Note that, by definition, none of the cyclic structures generates final goods and thus $\mathbf{f}^{*c,dir} = \mathbf{f}^{*c,ind} = \mathbf{0}_{n,1}$; and the acyclic–direct structure entails no inter-sectoral flows and thus $\mathbf{Z}^{*a,dir} = \mathbf{0}_{n,n}$ (as noted previously).

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
⋮		$\mathbf{Z}^{*c,ind}$		$\mathbf{0}_{n,1}$	$\mathbf{w}^{*c,ind}$	$\underline{\mathbf{x}}^{*c,ind}$
Sector n						
r		$\mathbf{r}^{*c,ind\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{*c,ind\prime}$				

TABLE 4.17: Simplified IO representation of the cyclic–indirect structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
⋮		$\mathbf{Z}^{*c,dir}$		$\mathbf{0}_{n,1}$	$\mathbf{w}^{*c,dir}$	$\underline{\mathbf{x}}^{*c,dir}$
Sector n						
r		$\mathbf{r}^{*c,dir\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{*c,dir\prime}$				

TABLE 4.18: Simplified IO representation of the cyclic–direct structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
⋮		$\mathbf{Z}^{*a,ind}$		$\mathbf{f}^{a,ind}$	$\mathbf{w}^{*a,ind}$	$\underline{\mathbf{x}}^{*a,ind}$
Sector n						
r		$\mathbf{r}^{*a,ind\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{*a,ind\prime}$				

TABLE 4.19: Simplified IO representation of the acyclic–indirect structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
⋮		$\mathbf{Z}^{*a,dir} = \mathbf{0}_{n,n}$		$\mathbf{f}^{a,dir}$	$\mathbf{w}^{*a,dir}$	$\underline{\mathbf{x}}^{*a,dir}$
Sector n						
r		$\mathbf{r}^{*a,dir\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{*a,dir\prime}$				

TABLE 4.20: Simplified IO representation of the acyclic–direct structural components.

The notation of tables 4.17, 4.18, 4.19 and 4.20 (and any IOT in general) can be further compressed so as to be used in equations. The corresponding compact notation of these tables are equations 4.31, 4.32, 4.33 and 4.33.

$$IOT^{c,ind} = \left(\frac{\mathbf{Z}^{*c,ind}}{\mathbf{r}^{*c,ind\prime}} \mid \mathbf{f}^{*c,ind} \mid \mathbf{w}^{*c,ind} \right) \tag{4.31}$$

$$IOT^{c,dir} = \left(\frac{\mathbf{Z}^{*c,dir}}{\mathbf{r}^{*c,dir\prime}} \mid \mathbf{f}^{*c,dir} \mid \mathbf{w}^{*c,dir} \right) \tag{4.32}$$

$$IOT^{a,ind} = \left(\frac{\mathbf{Z}^{*a,ind}}{\mathbf{r}^{*a,ind\prime}} \mid \mathbf{f}^{*a,ind} \mid \mathbf{w}^{*a,ind} \right) \tag{4.33}$$

$$IOT^{a,dir} = \left(\frac{\mathbf{Z}^{*a,dir}}{\mathbf{r}^{*a,dir\prime}} \mid \mathbf{f}^{*a,dir} \mid \mathbf{w}^{*a,dir} \right) \tag{4.34}$$

Then, tables 4.17, 4.18, 4.19 and 4.20 are re-written using the *non-simplified* notation consistent with the original decomposition of the inter-sectoral flows, as in table 4.16, because the calculations will require calculating each of the components shown in table 4.16, as well as their associated primary resources and emissions. This *non-simplified* notation will be used in section 4.5.2 to develop the method to calculate each sub-structure and re-aggregate them as the cyclic–acyclic and direct–indirect meta-structures. The *non-simplified* notation tables for each structure are:

- table 4.21 for the cyclic–indirect structure,
- table 4.22 for the acyclic–indirect structure,
- table 4.23 for the cyclic–direct structure, and
- table 4.24 for the acyclic–direct structure.

	Sector 1 ... Sector n	f	w	$\underline{x}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^{c,ind} + \mathbf{Z}^{ind,c} + \mathbf{Z}^{ind,ac,c}$	$\mathbf{0}_{n,1}$	$\mathbf{w}^{ind,c} + \mathbf{w}^{ind,ac,c}$	$\underline{\mathbf{x}}^{c,ind}$
r	$\mathbf{r}^{ind,ac,c\prime}$			
$\underline{x}$	$\underline{\mathbf{x}}^{c,ind\prime}$			

TABLE 4.21: Non-simplified IO representation of the cyclic–indirect structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
$\vdots$		$\mathbf{Z}^{c,dir}$		$\mathbf{0}_{n,1}$	$\mathbf{w}^{c,dir}$	$\underline{\mathbf{x}}^{c,dir}$
Sector n						
r		$\mathbf{r}^{c,dir\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{c,dir\prime}$				

TABLE 4.22: Non-simplified IO representation of the cyclic–direct structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
$\vdots$		$\mathbf{Z}^{ind,ac,a}$		$\mathbf{f}^{ind}$	$\mathbf{w}^{ind,ac,a}$	$\underline{\mathbf{x}}^{a,ind}$
Sector n						
r		$\mathbf{r}^{ind,ac,a\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{a,ind\prime}$				

TABLE 4.23: Non-simplified IO representation of the acyclic–indirect structural components.

	Sector 1	...	Sector n	f	w	$\underline{x}$
Sector 1						
$\vdots$		$\mathbf{0}_{n,n}$		$\mathbf{f}^{dir}$	$\mathbf{w}^{a,dir}$	$\underline{\mathbf{x}}^{a,dir}$
Sector n						
r		$\mathbf{r}^{a,dir\prime}$				
$\underline{x}$		$\underline{\mathbf{x}}^{a,dir\prime}$				

TABLE 4.24: Non-simplified IO representation of the acyclic–direct structural components.

4.5.1.4 Re-aggregating the four sub-structures into the two meta-structures and into the original structure

First, the method on how to aggregate the four substructures into the two meta-structures is demonstrated for any given structure. Then, this method is applied to aggregate the four substructures of the product-based structures into the four sub-structures of the original structure.

For a given structure Given the four sub-structural components (cyclic–indirect, cyclic–direct, acyclic–indirect and acyclic–direct, c.f. tables 4.21, 4.22, 4.23 and 4.24), the two meta-structures and the original structure can be calculated by re-aggregating the corresponding sub-structures.

To find the cyclic and acyclic components of the cyclic–acyclic meta-structure, the cyclic–direct and cyclic–indirect are aggregated to form the complete cyclic structure (equation 4.35) and the acyclic–direct and acyclic–indirect are aggregated to form the complete acyclic structure (equation 4.36).

$$\begin{aligned}
IOT^c &= IOT^{c,ind} + IOT^{c,dir} \\
&= \left(\begin{array}{c|c|c} \mathbf{Z}^{*c,ind} & \mathbf{f}^{*c,ind} & \mathbf{w}^{*c,ind} \\ \hline \mathbf{r}^{*c,ind\prime} & & \end{array} \right) + \left(\begin{array}{c|c|c} \mathbf{Z}^{*c,dir} & \mathbf{f}^{*c,dir} & \mathbf{w}^{*c,dir} \\ \hline \mathbf{r}^{*c,dir\prime} & & \end{array} \right) \\
&= \left(\begin{array}{c|c|c} \mathbf{Z}^{*c} & \mathbf{f}^{*c} & \mathbf{w}^{*c} \\ \hline \mathbf{r}^{*c\prime} & & \end{array} \right)
\end{aligned} \tag{4.35}$$

$$\begin{aligned}
IOT^a &= IOT^{a,ind} + IOT^{a,dir} \\
&= \left(\begin{array}{c|c|c} \mathbf{Z}^{*a,ind} & \mathbf{f}^{*a,ind} & \mathbf{w}^{*a,ind} \\ \hline \mathbf{r}^{*a,ind\prime} & & \end{array} \right) + \left(\begin{array}{c|c|c} \mathbf{Z}^{*a,dir} & \mathbf{f}^{*a,dir} & \mathbf{w}^{*a,dir} \\ \hline \mathbf{r}^{*a,dir\prime} & & \end{array} \right) \\
&= \left(\begin{array}{c|c|c} \mathbf{Z}^{*a} & \mathbf{f}^{*a} & \mathbf{w}^{*a} \\ \hline \mathbf{r}^{*a\prime} & & \end{array} \right)
\end{aligned} \tag{4.36}$$

Using the non-simplified components from tables 4.21, 4.22, 4.23 and 4.24, the non-simplified notation of the complete cyclic and acyclic meta-structures is provided, correspondingly, in tables 4.25 and 4.26. Note that $\mathbf{f}^{*c} = \mathbf{0}_{n,1}$ since the cyclic structure does not produce final goods.

	Sector 1 … Sector n	f	w	$\underline{x}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^c + \mathbf{Z}^{ind,c} + \mathbf{Z}^{ind,ac,c}$	$\mathbf{0}_{n,1}$	$\mathbf{w}^{c,dir} + \mathbf{w}^{ind,c} + \mathbf{w}^{ind,ac,c}$	$\underline{\mathbf{x}}^{c,ind} + \underline{\mathbf{x}}^{c,dir}$
r	$\mathbf{r}^{ind,ac,c\prime} + \mathbf{r}^{c,dir\prime}$			
$\underline{x}$	$\underline{\mathbf{x}}^{c,ind\prime} + \underline{\mathbf{x}}^{c,dir\prime}$			

TABLE 4.25: IO representation of the cyclic structure.

	Sector 1 … Sector n	f	w	$\underline{x}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^{ind,ac,a}$	$\mathbf{f}$	$\mathbf{w}^{ind,ac,a} + \mathbf{w}^{a,dir}$	$\underline{\mathbf{x}}^{a,ind} + \underline{\mathbf{x}}^{a,dir}$
r	$\mathbf{r}^{ind,ac,a\prime} + \mathbf{r}^{a,dir\prime}$			
$\underline{x}$	$\underline{\mathbf{x}}^{a,ind\prime} + \underline{\mathbf{x}}^{a,dir\prime}$			

TABLE 4.26: IO representation of the acyclic structure.

To find the direct and indirect components of the direct–indirect meta-structure, the cyclic–direct and acyclic–direct are aggregated to form the direct structure (equation 4.37) and the cyclic–indirect and acyclic–indirect are aggregated to form the indirect structure (equation 4.38). Note that $\mathbf{f}^{*a} = \mathbf{f}$ since the acyclic structure produces all final goods.

$$\begin{aligned} IOT^{dir} &= IOT^{c,dir} + IOT^{a,dir} \\ &= \left(\begin{array}{c|c|c} \mathbf{Z}^{*c,dir} & \mathbf{f}^{*c,dir} & \mathbf{w}^{*c,dir} \\ \hline \mathbf{r}^{*c,dir\prime} & & \end{array} \right) + \left(\begin{array}{c|c|c} \mathbf{Z}^{*a,dir} & \mathbf{f}^{*a,dir} & \mathbf{w}^{*a,dir} \\ \hline \mathbf{r}^{*a,dir\prime} & & \end{array} \right) \\ &= \left(\begin{array}{c|c|c} \mathbf{Z}^{*dir} & \mathbf{f}^{*dir} & \mathbf{w}^{*dir} \\ \hline \mathbf{r}^{*dir\prime} & & \end{array} \right) \end{aligned} \tag{4.37}$$

$$\begin{aligned} IOT^{ind} &= IOT^{c,ind} + IOT^{a,ind} \\ &= \left(\begin{array}{c|c|c} \mathbf{Z}^{*c,ind} & \mathbf{f}^{*c,ind} & \mathbf{w}^{*c,ind} \\ \hline \mathbf{r}^{*c,ind\prime} & & \end{array} \right) + \left(\begin{array}{c|c|c} \mathbf{Z}^{*a,ind} & \mathbf{f}^{*a,ind} & \mathbf{w}^{*a,ind} \\ \hline \mathbf{r}^{*a,ind\prime} & & \end{array} \right) \\ &= \left(\begin{array}{c|c|c} \mathbf{Z}^{*ind} & \mathbf{f}^{*ind} & \mathbf{w}^{*ind} \\ \hline \mathbf{r}^{*ind\prime} & & \end{array} \right) \end{aligned} \tag{4.38}$$

	Sector 1 … Sector n	f	w	$\underline{x}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^{c,dir}$	$\mathbf{f}^{dir}$	$\mathbf{w}^{c,dir} + \mathbf{w}^{a,dir}$	$\underline{\mathbf{x}}^{c,dir} + \underline{\mathbf{x}}^{a,dir}$
r	$\mathbf{r}^{c,dir\prime} + \mathbf{r}^{a,dir\prime}$			
$\underline{x}$	$\underline{\mathbf{x}}^{c,dir\prime} + \underline{\mathbf{x}}^{a,dir\prime}$			

Table 4.27: IO representation of the direct structure.

	Sector 1 … Sector n	f	w	$\underline{x}$
Sector 1 ⋮ Sector n	$\mathbf{Z}^{c,ind} + \mathbf{Z}^{ind,c} + \mathbf{Z}^{ind,ac}$	$\mathbf{f}^{ind}$	$\mathbf{w}^{ind,c} + \mathbf{w}^{ind,ac,a} + \mathbf{w}^{ind,ac,c}$	$\underline{\mathbf{x}}^{c,ind} + \underline{\mathbf{x}}^{a,ind}$
r	$\mathbf{r}^{ind,ac,a\prime} + \mathbf{r}^{ind,ac,c\prime}$			
$\underline{x}$	$\underline{\mathbf{x}}^{c,ind\prime} + \underline{\mathbf{x}}^{a,ind\prime}$			

Table 4.28: IO representation of the indirect structure.

Finally, the aggregated structure can be found either by re-aggregating the four sub-structures (equation 4.39) , the cyclic–acyclic meta-structure (equation 4.40) or the direct–indirect meta-structure (equation 4.41).

$$IOT = IOT^{c,ind} + IOT^{a,ind} + IOT^{c,dir} + IOT^{a,dir} \tag{4.39}$$

$$IOT = IOT^{c} + IOT^{a} \tag{4.40}$$

$$IOT = IOT^{dir} + IOT^{ind} \tag{4.41}$$

Application to the product-based structures In this section, it is assumed that the meta-structural decomposition has been applied to each product-based structure, so it is shown how to re-aggregate the four sub-structures of each product-based structure into the four sub-structures of the original structure.

Since each product-based structure can be decomposed into the four sub-structures of the two meta-structures (equation 4.39) and the aggregate structure is a linear combination of the n product-based structures (c.f. equation 4.17), each of the four sub-structures of the aggregate structure can also be found by aggregating the corresponding sub-structures of the product-based structures, as demonstrated below in equation 4.42. Then, using equations 4.35, 4.36, 4.37 and 4.38, the two meta-structures of the original structure can be reconstituted (c.f. equations 4.43 and 4.44).

$$
\begin{aligned}
{}^{agg}IOT &= \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT \\
&= \sum_{p=1}^{n} f_p \cdot ({}^{s_p}IOT^{c,dir} + {}^{s_p}IOT^{c,ind} + {}^{s_p}IOT^{a,dir} + {}^{s_p}IOT^{a,ind}) \\
&= \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT^{c,dir} + \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT^{c,ind} + \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT^{a,dir} + \sum_{p=1}^{n} f_p \cdot {}^{s_p}IOT^{a,ind} \\
&= {}^{agg}IOT^{c,dir} + {}^{agg}IOT^{c,ind} + {}^{agg}IOT^{a,dir} + {}^{agg}IOT^{a,ind} && (4.42) \\
&= {}^{agg}IOT^{c} + {}^{agg}IOT^{a} && (4.43) \\
& or \\
&= {}^{agg}IOT^{dir} + {}^{agg}IOT^{ind} && (4.44)
\end{aligned}
$$

4.5.2 Method to decompose the production structure between its four sub-structures (direct–cyclic, cyclic–indirect, acyclic–indirect and direct–cyclic)

Due to how the two meta-structures are interlaced, there is an order to derive the four sub-structures: first, the cyclic–indirect and acyclic–indirect structures are derived in a common process, then the cyclic–direct structure and, finally, the acyclic–direct structure. The order is given by the information available at any one time: e.g. the first available structural components are $\mathbf{Z}^c$ and $\mathbf{Z}^{ind}$. Then with $\mathbf{Z}^c$, the cycling throughput can be calculated and with it $\mathbf{Z}^{ind}$ can be decomposed into $\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac}$. Only then, the corresponding resources required by $\mathbf{Z}^{ind,ac}$, i.e. $\mathbf{r}^{ind,ac}$, can be calculated.

The next sub-sections develop the methods to calculate each sub-structure; the notation follows the one used in tables 4.21, 4.22, 4.23 and 4.24.

The decompositions developed below are to be applied to product-based structures — never to the original, aggregated structure (c.f. sections 4.2.2 and 4.2.3). However, for readability, the prepended superscript s_p denoting the product-based structure of product p is avoided in all variables of this section.

Note that the previous decomposition has been developed on a PIOT where final demand is exogenous. The method has been developed on this IO framework, i.e. on a system representing the productive structure, to identify exclusively the systemic effects of pre-consumer cycling. This choice was taken because extending the framework to capture the systemic effects of post-consumer cycling would require modifying the PIOT to endogenise the final demand sector, which would lead to two main drawbacks: first, the method developed would not be directly applicable to conventional PIOTs, potentially limiting the application of the method; and, second, it was unknown whether the systemic impacts of post-consumer cycling would be clearly separated from the pre-consumer cycling ones.

All the calculations of this section have been integrated in the software developed during this research: Metab-X (c.f. appendix C).

4.5.2.1 Finding the cyclic–indirect and acyclic–indirect structures

Decomposing $\mathbf{Z}^{ind}$ between $\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac}$ The decomposition of $\mathbf{Z}^{ind}$ uses the assumption of homogeneous goods' production already implied in IO models, i.e. the final and intermediate goods of a given sector are the same, in turn implying for all sectoral production the same input "recipe". Thus, each sector's specific combination of inputs — the "recipe" — are allocated proportionally to the amount of goods produced.

So, knowing the amount of goods produced, the amount of inputs required for the production of a specific amount of goods can be calculated according to the output proportion of the output regarding the total output. Thus, the proportion of inputs required for cycling, final goods and indirect acyclic are calculated as follows

$$prop(c_i) = \frac{c_i}{f_i + \sum_{j=1}^{n} z_{ij}^{ind} + c_i} \tag{4.45}$$

$$prop(f_i) = \frac{f_i}{f_i + \sum_{j=1}^{n} z_{ij}^{ind} + c_i} \tag{4.46}$$

$$prop(z_i) = \frac{\sum_{j=1}^{n} z_{ij}^{ind}}{f_i + \sum_{j=1}^{n} z_{ij}^{ind} + c_i} \tag{4.47}$$

The proportions for intermediate acyclic goods $prop(z_i)$ and final goods $prop(f_i)$ belong to the indirect structure $\mathbf{Z}^{ind,ac}$ because the acyclic–direct does not have intersectoral flows, so they can be aggregated as the proportion for indirect flows as

$$prop(ac_i) = \frac{f_i + \sum_{j=1}^{n} z_{ij}^{ind}}{f_i + \sum_{j=1}^{n} z_{ij}^{ind} + c_i} \tag{4.48}$$

The proportions can then be used to allocate $\mathbf{Z}^{ind}$ between $\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac}$ as follows:

$$\mathbf{Z}^{ind,c} = \mathbf{Z}^{ind} \cdot \widehat{prop(\mathbf{c})} \tag{4.49}$$

$$\mathbf{Z}^{ind,ac} = \mathbf{Z}^{ind} \cdot \widehat{prop(\mathbf{ac})} \tag{4.50}$$

Calculating $\mathbf{r}^{ind,ac}$ $\mathbf{Z}^{ind,ac}$ represents the indirect structure that feeds the cyclic and acyclic flows; thus, by definition, the direct use of primary resources for either cyclic or final flows is prohibited. Since $\mathbf{Z}^{ind,ac}$ entails no cyclic flows, one can derive the resources required to maintain it by using the traditional resource efficiency rules. However, the amount of primary resources required to generate the indirect flows are mitigated by the intermediate flows used for production. So, each sector requires resources to produce the indirect flows (row sum of $\mathbf{Z}^{ind,ac}$) and to produce the resources that feed the cyclic flows indirectly (row sum of $\mathbf{Z}^{ind,c}$), but these requirements are mitigated by the use of the intermediate inputs from $\mathbf{Z}^{ind,ac}$ itself (column sum of $\mathbf{Z}^{ind,ac}$).

To make it clearer, the reasoning is formalised by using the mass balance principle. The inputs and outputs are related to the same sector; thus, the sector indices $i = j$ when representing the inputs (given in column j) and outputs (given in the corresponding row i) of a given sector.

$$inputs_j = outputs_i \tag{4.51}$$

$$primary\ inputs_j + intermediate\ inputs_j = intermedisate\ goods_i + final\ goods_i + emissions_i \tag{4.52}$$

In IO notation:

$$r_j + \sum_{i=1}^{n} z_{ij} = \sum_{j=1}^{n} z_{ij} + f_i + w_i \tag{4.53}$$

Thus, the sectoral resource efficiency can be defined using equation 4.53, as follows:

$$\eta_i = \frac{\sum_{j=1}^{n} z_{ij} + f_i}{r_j + \sum_{i=1}^{n} z_{ij}} \tag{4.54}$$

Equation 4.54 can be used to relate the inputs to useful outputs (either intermediate or final). Applying equation 4.54 to the indirect structure (c.f equation 4.28) where the re-used inputs stem from $\mathbf{Z}^{ind,ac}$ alone because $\mathbf{Z}^{ind,c}$ is fully consumed to maintain cycling indirectly:

$$(r_j^{ind,ac} + \sum_{i=1}^{n} z_{ij}^{ind,ac}) \cdot \eta_j = \sum_{j=1}^{n} z_{ij}^{ind,c} + \sum_{j=1}^{n} z_{ij}^{ind,ac} + f_i^{ind} \tag{4.55}$$

$$\begin{aligned} r_j^{ind,ac} &= \frac{\sum_{j=1}^{n} z_{ij}^{ind,c} + \sum_{j=1}^{n} z_{ij}^{ind,ac} + f_i^{ind}}{\eta_j} - \sum_{i=1}^{n} z_{ij}^{ind,ac} \\ r_j^{ind,ac} &= \frac{\sum_{j=1}^{n} z_{ij}^{ind} + f_i^{ind}}{\eta_j} - \sum_{i=1}^{n} z_{ij}^{ind,ac} \end{aligned} \tag{4.56}$$

Calculating $\mathbf{f}^{ind}$ Only one final good is produced in each product-based structure and, by definition, it is known which sector is producing it. Also, by definition, the acyclic–indirect structure does not entail primary resources for the sector producing the final good (otherwise the final good would not be produced indirectly) and ,thus, $\mathbf{f}^{ind}$ is produced totally from intermediate flows, i.e. no primary resource is fed into the sector producing the final good.

However, at this point, only $\mathbf{Z}^{ind,ac}$ is known — which contains flows for the cyclic–indirect and acyclic–indirect structure; so, how to find which flows belong to the acyclic structure only and how to find $\mathbf{f}^{ind}$?

The key is that the flows from $\mathbf{Z}^{ind,ac}$ that are used to produce $\mathbf{f}^{ind}$ can be identified directly. For sector p only, the input structure from $\mathbf{Z}^{ind,ac}$ (i.e. the p^{th} column) corresponds to the input structure of $\mathbf{Z}^{ind,ac,a}$ because there is no need to bring resource to sector p to be carried forward for cycling purposes. In other words, the resources used to feed cycling indirectly are provided by $\mathbf{Z}^{ind,c}$ and there is no need to bring more resources for posterior use since the p sector is the “last” sector — i.e. the one producing the final good. Thus, for $j = p$

$$z_{ip}^{ind,ac,a} = z_{ip}^{ind,ac} \ , \ \forall i \epsilon \ [0, n] \tag{4.57}$$

Consequently, $\mathbf{f}^{ind}$ can be calculated from the intermediate resources $\mathbf{Z}^{ind,ac}$ used by sector p since all those intermediate resources have the only purpose of producing the final good. Thus,

$$f_p^{ind} = \eta_p \cdot \sum_{i=1}^{n} z_{ip}^{ind,ac} \tag{4.58}$$

Decomposing $\mathbf{Z}^{ind,ac}$ between $\mathbf{Z}^{ind,ac,a}$ and $\mathbf{Z}^{ind,ac,c}$ and finding the corresponding primary resources $\mathbf{r}^{ind,ac,a}$ and $\mathbf{r}^{ind,ac,c}$ By definition, $\mathbf{Z}^{ind,ac,a}$ constitutes the flows ultimately embedded in final goods through the indirect structure, exiting the system as $\mathbf{f}^{ind}$. The remainder of the $\mathbf{Z}^{ind,ac}$ structure — i.e. $\mathbf{Z}^{ind,ac,c}$ — corresponds to the flows used to "bring" resources to $\mathbf{Z}^{ind,c}$ so they can feed part of the cyclic structure $\mathbf{Z}^{c}$ indirectly ($\mathbf{Z}^{c,ind}$).

Since the $\mathbf{Z}^{ind,ac}$ structure only entails non-cyclic flows, the sectors can be ordered so that the sectors providing the goods with a lower degree of fabrication appear first and the sector producing final goods is the last one. Ordering a three sector network, the sector extracting the primary resource is the first sector, the intermediate sector transforming the primary resource into an intermediate good is the second, and the sector transforming the intermediate good into a final good is the last. Networks can be much more complex with several sectors providing intermediate goods simultaneously for different stages of production; however, if the network is acyclic, it can always be arranged in such ordered manner. In IOA, this would correspond to rearranging the IOT as a *triangular matrix*; in graph theory, this ordering is done through a *topological ordering*.

Arranging the sectors in topological order allows for decomposing $\mathbf{Z}^{ind,ac}$ between $\mathbf{Z}^{ind,ac,a}$ and $\mathbf{Z}^{ind,ac,c}$ since it makes it possible to backtrack the resources required indirectly to produce final goods $\mathbf{f}^{ind}$, the only final good of the structure.

The backtracking algorithm developed below follows the homogeneous goods assumption implied in IOA, i.e. that each sector requires the same input recipe, so that, a proportional relationship between the outputs and the inputs can be established.

Before deriving the proportional relationship, the topological ordering is illustrated for an hypothetical example together with the illustration of the resulting network and its sub-components. The hypothetical example represents the product-based structure of product one (hence sector one is the only one producing final goods and not using primary resources) with sector three providing intermediate goods to sector one, and sector two providing intermediate goods to sectors one and three.

The *topological order* of the sectors would be sector two, three and one because sector three provides to sector one (and is hence before sector one); sector two provides sector three and one (and is hence before sector three and one); since three is before one and two is before three and one, the final order is two, three, one. In this case, the ordering was unique but in some cases it might be non-unique[19]; the non-uniqueness does not affect the results of the backtracking process because, as long as a topological order exists, the topological order guarantees that the precedent flows can be calculated.

[19] Acyclic networks can always be topologically ordered although there might be several solutions. E.g. a three sectors product-one-based network where only sectors two and three provide intermediate goods to sector one. Since there is no relationship between two and three, their order is not relevant and there are two topological orderings: sectors two, three, one or three, two, one.

A hypothetical product-based structure for product one is presented in table 4.29 and its topologically ordered counterpart as table 4.30 (note the inter-sectoral matrix is right-triangular). The network sorted in topological order is drawn in figure 4.10, with the flows belonging to $\mathbf{Z}^{ind,ac}$ represented in white boxes. The components of $\mathbf{Z}^{ind,c}$ are also included as grey boxes to explain the decomposition rationale. Note that the ordering has arranged the flows so they only flow in one direction (upwards). Then, it becomes clear that knowing the relationship between sectoral inputs and outputs, it is possible to quantify all flows of the structure by knowing the "top" flow, f_1^{ind} in this case.

	Sector 1	Sector 2	Sector 3	f	w
Sector 1	0	0	0	f_1^{ind}	$w_1^{ind,ac}$
Sector 2	$z_{21}^{ind,ac}$	0	$z_{23}^{ind,ac}$	0	$w_2^{ind,ac}$
Sector 3	$z_{31}^{ind,ac}$	0	0	0	$w_3^{ind,ac}$
r	0	$r_2^{ind,ac}$	$r_3^{ind,ac}$		

Table 4.29: Hypothetical example representing the indirect structure of a product-based structure of product one.

	Sector 2	Sector 3	Sector 1	f	w
Sector 2	0	$z_{23}^{ind,ac}$	$z_{21}^{ind,ac}$	0	$w_2^{ind,ac}$
Sector 3	0	0	$z_{31}^{ind,ac}$	0	$w_3^{ind,ac}$
Sector 1	0	0	0	f_1^{ind}	$w_1^{ind,ac}$
r	$r_2^{ind,ac}$	$r_3^{ind,ac}$	0		

Table 4.30: Hypothetical example representing the indirect structure of a product-based structure of product one in topological order.

Figure 4.10 is now used to illustrate how the intermediate flows can be backtracked. Recall that the flows $\mathbf{Z}^{ind,c}$ are used by the sector to maintain the cycling and are thus consumed totally without producing any good. The indirect flows reaching the last sector ($z_{21}^{ind,ac}$ and $z_{31}^{ind,ac}$) contain only acyclic flows since there is no cycling to be fed after the last sector, hence the c component of $z_{21}^{ind,ac}$ and $z_{31}^{ind,ac}$ have been cancelled. In other words, the flows reaching the last sector ($z_{21}^{ind,ac}$ and $z_{31}^{ind,ac}$) are totally used for acyclic purposes (i.e. to produce f^{ind}).

Generalising the reasoning: due to the homogeneous goods assumption, the proportions are relative to the output but applied to the inputs. Thus, the proportions to allocate $z^{ind,ac}$ between $z^{ind,ac,a}$ and $z^{ind,ac,c}$ are based on the total outputs, as follows:

$$prop(c) = \frac{cyclic\ outputs\ (from\ \mathbf{Z}^{ind,c}\ and\ \mathbf{Z}^{ind,ac,c})}{total\ outputs\ (from\ \mathbf{Z}^{ind,c},\ \mathbf{Z}^{ind,ac,c}\ and\ \mathbf{Z}^{ind,ac,a})} \tag{4.59}$$

$$prop(a) = \frac{acyclic\ outputs\ (from\ \mathbf{Z}^{ind,ac,a})}{total\ outputs\ (from\ \mathbf{Z}^{ind,c},\ \mathbf{Z}^{ind,ac,c}\ and\ \mathbf{Z}^{ind,ac,a})} \tag{4.60}$$

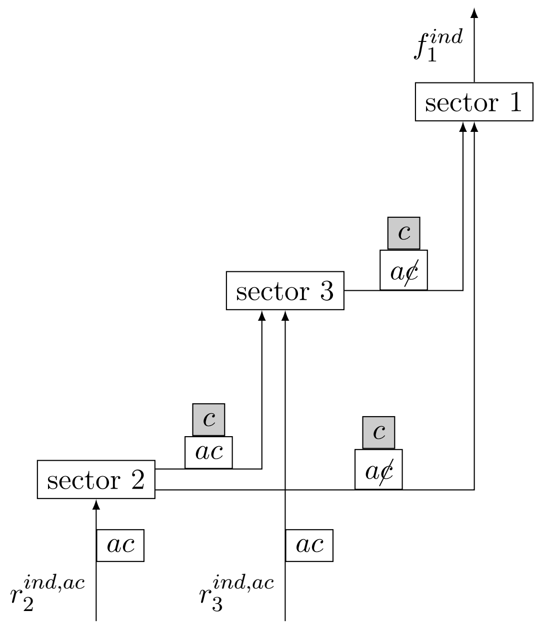

FIGURE 4.10: Network representation of a topologically ordered product-based structure. The boxes besides the arrows show the type of flow that is conveyed: the white ones belong to $\mathbf{Z}^{ind,ac}$ (corresponding to table 4.30) and the grey boxes belong to $\mathbf{Z}^{ind,c}$; the emissions are omitted for clarity.

Next, this reasoning is applied to sector one of figure 4.10:

- the output used for cycling equals 0 since it is the last sector
- the output used for acyclic flows equals f^{ind} since it is the last sector

which applied to find the amount of inputs dedicated to each structure gather:

$$z_{21}^{ind,ac,a} = z_{21}^{ind,ac} \cdot \frac{f^{ind}}{f^{ind}} = z_{21}^{ind,ac} \tag{4.61}$$

$$z_{21}^{ind,ac,c} = z_{21}^{ind,ac} \cdot \frac{0}{f^{ind}} = 0 \tag{4.62}$$

$$z_{31}^{ind,ac,a} = z_{31}^{ind,ac} \cdot \frac{f^{ind}}{f^{ind}} = z_{31}^{ind,ac} \tag{4.63}$$

$$z_{31}^{ind,ac,c} = z_{31}^{ind,ac} \cdot \frac{0}{f^{ind}} = 0 \tag{4.64}$$

The results for the "last" sector — which corresponds to sector p — ratifies the explanation provided in previous sub-section (pg. 172) to find $\mathbf{f}^{ind}$.

Once one set of outputs is known, since there is a fixed relationship between the outputs and inputs (provided by equations 4.59 and 4.60), the next set of sectoral inputs can be calculated, as long as they are in topological order, which is the case. Following this logic, the next sector is sector three from which the proportions of $z_{23}^{ind,ac}$ and $r_3^{ind,ac}$ are sought. Its total output is $z_{31}^{ind,c} + z_{31}^{ind,ac,a}$, of which only $z_{31}^{ind,c}$ contributes to cycling, so:

$$z_{23}^{ind,ac,a} = z_{23}^{ind,ac} \cdot \frac{z_{31}^{ind,ac,a}}{z_{31}^{ind,c} + z_{31}^{ind,ac,a} + z_{31}^{ind,ac,c}} \tag{4.65}$$

$$z_{23}^{ind,ac,c} = z_{23}^{ind,ac} \cdot \frac{z_{31}^{ind,c} + z_{31}^{ind,ac,c}}{z_{31}^{ind,c} + z_{31}^{ind,ac,a} + z_{31}^{ind,ac,c}} \tag{4.66}$$

The same proportions can be applied to the primary resources, as follows:

$$r_{3}^{ind,ac,a} = r_{3}^{ind,ac} \cdot \frac{z_{31}^{ind,ac,a}}{z_{31}^{ind,c} + z_{31}^{ind,ac,a} + z_{31}^{ind,ac,c}} \tag{4.67}$$

$$r_{3}^{ind,ac,c} = r_{3}^{ind,ac} \cdot \frac{z_{31}^{ind,c} + z_{31}^{ind,ac,c}}{z_{31}^{ind,c} + z_{31}^{ind,ac,a} + z_{31}^{ind,ac,c}} \tag{4.68}$$

In equations 4.65 to 4.68, all variables are included to reveal the pattern of the methodology even if some equal 0 (as $z_{31}^{ind,ac,c}$ and $z_{21}^{ind,ac,c}$).

Finally, the primary resources feeding sector 2 can be decomposed; its total output is $z_{23}^{ind,ac,a} + z_{23}^{ind,ac,c} + z_{23}^{ind,c} + z_{21}^{ind,ac,a} + z_{21}^{ind,c}$, thus

$$r_{2}^{ind,ac,a} = r_{2}^{ind,ac} \cdot \frac{z_{23}^{ind,ac,a} + z_{21}^{ind,ac,a}}{z_{23}^{ind,ac,a} + z_{23}^{ind,ac,c} + z_{23}^{ind,c} + z_{21}^{ind,ac,a} + z_{21}^{ind,ac,c} + z_{21}^{ind,c}} \tag{4.69}$$

$$r_{2}^{ind,ac,c} = r_{2}^{ind,ac} \cdot \frac{z_{23}^{ind,ac,c} + z_{23}^{ind,c} + z_{21}^{ind,ac,c} + z_{21}^{ind,c}}{z_{23}^{ind,ac,a} + z_{23}^{ind,ac,c} + z_{23}^{ind,c} + z_{21}^{ind,ac,a} + z_{21}^{ind,ac,c} + z_{21}^{ind,c}} \tag{4.70}$$

Calculating $\mathbf{w}^{ind,ac,a}$, $\mathbf{w}^{ind,ac,c}$ and $\mathbf{w}^{ind,c}$ Recalling tables 4.21 and 4.23, the emissions corresponding to the acyclic–indirect are $\mathbf{w}^{ind,ac,a}$ and the ones corresponding to the cyclic–indirect are $\mathbf{w}^{ind,ac,c}$ and $\mathbf{w}^{ind,c}$. This sub-section shows how to calculate them.

$\mathbf{w}^{ind,ac,a}$ and $\mathbf{w}^{ind,ac,c}$ can be calculated by using the sectoral efficiency (c.f. equation 4.54): the total sectoral inputs of the targeted structure are multiplied by $1-\eta$, as follows:

$$w_{j}^{ind,ac,a} = \left(\sum_{i=1}^{n} z_{ij}^{ind,ac,a} + r_{j}^{ind,ac,a} \right) \cdot (1-\eta_j) \tag{4.71}$$

$$w_{j}^{ind,ac,c} = \left(\sum_{i=1}^{n} z_{ij}^{ind,ac,c} + r_{j}^{ind,ac,c} \right) \cdot (1-\eta_j) \tag{4.72}$$

$\mathbf{w}^{ind,c}$ is a special case since the emissions due to cycling equal the resources used for cycling (c.f. equation 4.25). Thus, since $\mathbf{Z}^{ind,c}$ represents the resources indirectly used to maintain cycling:

$$w_j^{ind,c} = \sum_{i=1}^{n} z_{ij}^{ind,c} \tag{4.73}$$

At this point, all components of the indirect-cyclic and acyclic–indirect structures have been calculated.

However, since the emissions are calculated from the inputs, the result represents the total emissions generated as an aggregate. In the case where the PIOT includes different emissions types, each emission type can be found by using equation 3.46 in equation 4.9: since $\mathbf{w}^{ind,c}$, $\mathbf{w}^{ind,ac,c}$ and $\mathbf{w}^{ind,ac,a}$, $\mathbf{E}_{tot}$ are known, the total outputs associated to each output structure can be found; then, using $\mathbf{E}_{1,\ldots,n}$ (c.f. equation 3.46), the emissions for each emission type can be found for each meta-structure.

4.5.2.2 Finding the cyclic–direct structure

Calculating $\mathbf{r}^{c,dir}$ and $\mathbf{w}^{c,dir}$ The total cyclic flows $\mathbf{Z}^c$ are known (and thus, the total cycling throughput); however, since some cycles are fed indirectly by $\mathbf{Z}^{ind,c}$, the part of $\mathbf{Z}^c$ fed directly is unknown and thus $\mathbf{Z}^{c,dir}$, $\mathbf{r}^{c,dir}$ and $\mathbf{w}^{c,dir}$ remain unknown.

The resources that feed cycling indirectly are the ones provided by $\mathbf{Z}^{ind,c}$ and thus are not primary resources but are the intermediate resources provided to each sector to maintain the cycling. They are denoted $\mathbf{vr}^{c,ind}$ for "virtual resources" since they do not actually belong to the primary resources but they can be understood as primary resources brought indirectly to the cyclic structure.

$$vr_j^{c,ind} = \sum_{i=1}^{n} z_{ij}^{ind,c} \tag{4.74}$$

Recalling the relationship between the cycling throughput and the resources required by it (equation 4.25); equation 4.75 reveals the cycling throughput that is fed indirectly c_i^{ind} by using the virtual resources fed indirectly $\mathbf{vr}^{c,ind}$:

$$c_j^{ind} = \frac{vr_j^{c,ind} \cdot \eta_j}{(1-\eta_j)} \tag{4.75}$$

Then the cycling throughput fed directly can be calculated as

$$c_j^{dir} = c_j - c_j^{ind} \tag{4.76}$$

Finally, using equation 4.25 with c_j^{dir}, the resources and emissions of the cyclic–direct structure are:

$$r_j^{c,dir} = w_j^{c,dir} = \frac{c_j^{dir} \cdot (1-\eta_j)}{\eta_j} \tag{4.77}$$

The emissions $w^{c,dir}$ are aggregated but can be disaggregated for each emission type following the same method suggested in the previous sub-section.

4.5.2.3 Finding the acyclic–direct structure

At this point, only $\mathbf{f}^{dir}$, $\mathbf{r}^{a,dir}$ and $\mathbf{w}^{a,dir}$ from table 4.24 remain to be calculated.

First, $\mathbf{r}^{a,dir}$ is calculated as the remainder of the primary resources used by the other structures:

$$r_i^{a,dir} = r_i - r_i^{c,dir} - r_i^{ind,ac,a} - r_i^{ind,ac,c} \tag{4.78}$$

$\mathbf{f}^{dir}$ can be calculated in two different ways so obtaining the same results confirms that the decomposition between the four sub-structures is consistent.

$$f_i^{dir} = f_i - f_i^{ind} \tag{4.79}$$

$$f_i^{dir} = r_i^{a,dir} \cdot \eta_i \tag{4.80}$$

$\mathbf{w}^{a,dir}$ can also be calculated in two different ways so obtaining the same results confirms that the decomposition between the four sub-structures is consistent.

The first manner is by subtracting the emissions of all other sub-structures to the total emissions (equation 4.81); the second manner is by using the sectoral resource efficiency of each sector since the primary resources are directly transformed into final goods (equation 4.82).

$$w_i^{a,dir} = w_i - w_i^{c,dir} - w_i^{ind,c} - w_i^{ind,ac,a} - w_i^{ind,ac,c} \tag{4.81}$$

$$w_i^{a,dir} = r_i^{a,dir} \cdot (1-\eta_i) \tag{4.82}$$

4.6 Additional notes on the structural decomposition

4.6.1 On the self-cycling and inter-cycling components of the cyclic matrix

4.6.1.1 Aggregation issues

The sectoral *cycling throughput* can be further sub-divided between the cycles going through the same sector, indicated as $\mathbf{c}^{self}$ (*self-cycling throughput*), and the cycles going through the rest of the economy, indicated as $\mathbf{c}^{inter}$ (*inter-cycling throughput*). The *self-cycling throughput* has the analytical meaning that some sectors need to use some of their own production to keep producing (e.g. the agricultural sector reserves part of the crop as seeds and fertiliser for the next crop). Unfortunately, *self-cycles* can also mask *inter-cycles* when a sector aggregates several sectors linked by cycling or even acyclic flows between different sectors that are aggregated under the same sector. However, inter-cycling does not mask any acyclic flows.

Analytically, the *self-cycles* correspond to the flows of the diagonal of $\mathbf{Z}^c$; thus $\mathbf{Z}^{c,self}$ is a diagonal matrix where its diagonal elements equal those of $\mathbf{Z}^c$ and the rest are zero, i.e.:

$$z_{i,j}^{c,self} = \begin{cases} z_{i,j}^c & \forall i = j \\ 0 & \forall i \neq j \end{cases} \tag{4.83}$$

The inter-cycling flows correspond to the rest of the cycling flows, thus

$$\mathbf{Z}^{c,inter} = \mathbf{Z}^c - \mathbf{Z}^{c,self} \tag{4.84}$$

and the corresponding self-cycling and inter-cycling throughputs are

$$\mathbf{c}^{self} = \mathbf{Z}^{c,self} \cdot \mathbf{i} = \mathbf{i} \cdot \mathbf{Z}^{c,self} \tag{4.85}$$

$$\mathbf{c}^{inter} = \mathbf{Z}^{c,inter} \cdot \mathbf{i} = \mathbf{i} \cdot \mathbf{Z}^{c,inter} \tag{4.86}$$

The corresponding primary resources ($\mathbf{r}^{c,self}$ and $\mathbf{r}^{c,inter}$) and emissions ($\mathbf{w}^{c,self}$ and $\mathbf{w}^{c,inter}$) can be calculated using equation 4.25.

So, it is expected that cycling indicators are sensitive to the level of aggregation since, as argued for the case of *self-cycling*, the cycling throughput through a compartment can vary depending on the level of aggregation. Finn (1976) also noted that "TST [total system throughput] is sensitive to the number of compartments"; so, the FCI is also sensitive to the aggregation level.

4.6.1.2 The Cyclic Connectivity indicator

On the other hand, the *inter-cycling throughput* always represents the cycling flows that are exchanged between different sectors and, thus, conveys explicitly the degree of cyclic linkage of a sector with the rest of the economy. In other words, the more inter-cycling throughput exists through a given sector, the more this sector is linked to other sectors by cyclic exchanges. Thus, a change in the total production or efficiency of that sector will affect the whole system through the inter-cycling linkage. Conversely, the more self-cycling throughput exists, the more the cycling effects are self-contained within the same sector and do not spread through the system. Thus, it is interesting to know the proportion of inter-cycling throughput flowing through a given sector because it can be used as a proxy for the systemic effects associated with cycling; this proportion is hereafter called the Cyclic Connectivity.

The Cyclic Connectivity (CC) indicator of sector i can be defined as the ratio between the inter-cycling throughput flowing through that sector (see equation 4.86) and its total cycling throughput:

$$CC_i = \frac{c_i^{inter}}{c_i} \tag{4.87}$$

The higher the CC indicator of a given sector is, the more inter-sectoral cycles linking that sector to the rest of the system exist and, thus, more systemic effects can be expected if that sector activity is modified.

4.6.2 On the direct and indirect components of the cyclic matrix

In the previous section 4.5.2, all components enabling finding the direct–indirect and cyclic–acyclic meta-structures have been calculated except the direct and indirect components of the cyclic matrix $\mathbf{Z}^{c,dir}$ and $\mathbf{Z}^{c,ind}$. These missing components are not required to calculate the other components of the direct–indirect and cyclic–acyclic meta-structures which are calculated from the direct and indirect cycling throughput. However, this implies that the intersectoral components of the direct–indirect meta-structure are missing.

No method to decompose $\mathbf{Z}^c$ into $\mathbf{Z}^{c,dir}$ and $\mathbf{Z}^{c,ind}$ has been developed because no direct relationship between the sectoral cycling throughput and total cycling could be established. The direct and indirect cycling throughput were calculated to find $\mathbf{r}^{c,dir}$ and $\mathbf{w}^{c,dir}$. However, it is unknown which cyclic structure is associated to these cycling throughputs, i.e. which cycles compose these cycling throughputs. Since the cyclic–acyclic meta-structure has already been fully identified, the decomposition of $\mathbf{Z}^c$ between $\mathbf{Z}^{c,dir}$ and $\mathbf{Z}^{c,ind}$ only affects the identification of the intersectoral direct and indirect structures, and thus has reduced impact on the structural analysis, especially since the analytical focus here is on the cyclic structure.

4.6.3 On identifying the pre-consumer and post-consumer cycling structures

The methodology developed in section 4.5 to identify the complete cyclic structure within a physical input-output table (PIOT) could be used to identify both pre-consumer and post-consumer cycling. In traditional PIOTs, final demand is exogenous; thus, all cycling identified corresponds to pre-consumer cycling since the household sector is "out" of the system.

However, traditional IOTs can be altered so as to include, i.e. endogenise, the final consumption sectors (Miyazawa, 1976; Miller and Blair, 2009). In this case, both pre-consumer or post-consumer cycling would be captured. By definition, post-consumer cycling includes all simple cycles involving final goods and services (c.f. section 4.4.4). Thus, in order to differentiate post-consumer cycling from pre-consumer cycling, the algorithm identifying cycling should be modified to create two cycling arrays, one for each type of cycling. The algorithm would need to check whether each simple cycle identified contains (i.e. passes through) a final demand sector (i.e. the household, government or gross capital formation sectors). If so, the algorithm would allocate the whole cycle to the post-consumer cycling array; if not, the algorithm would allocate the whole cycle to the pre-consumer cycling array. So, total cycling is composed by pre-consumer and post-consumer inter-sectoral cycles, as follows:

$$\mathbf{Z}^{c} = \mathbf{Z}^{pre-consumer\ cycling} + \mathbf{Z}^{post-consumer\ cycling} \tag{4.88}$$

However, the modifications of the method developed in order to quantify post-consumer cycling are not further explored since they would require to reformulate the method and it would divert the focus of the research from assessing the systemic impacts associated to pre-consumer cycling.

Chapter 5

Developing indicators and macroscopic-mesoscopic relationships associated to the cyclic and indirect sub-structures

5.1 Introduction

The aim of this chapter is to develop indicators that can be used to quantify the environmental impact of the cyclic and indirect sub-structures (which are the structures generating more indirect effects through system interactions, compared to the acyclic and direct sub-structures), and to develop theoretical relationships between these sub-structures and the emissions levels and resource efficiency of the overall system. Such indicators and relationships would inform which structural changes are to be pursued to improve the resource efficiency of the economic system by altering its structure.

First, in section 5.2, it is discussed how the macroscopic behaviour of the economic system can be linked and explained using a lower degree of observation In this case, since the analytical framework is IOA, the lower degree of observation corresponds to the sectoral structure, constituting a mesoscopic approach and level of observation.

Then, a similar set of indicators for the cyclic and indirect sub-structures are developed in section 5.3 to quantify the weight and influence of these structures on the system. Such indicators can then be used to assess the impact of the cyclic structure on the environmental performance of the system, e.g., by quantifying the amount of emissions associated to the cyclic structure.

Finally, in section 5.4, the macroscopic resource efficiency and emissions are algebraically related to the different structural components. Establishing such relationships is important because it enables researchers to understand how each sub-structural component affects the overall environmental performance of the system. More importantly, it allows the determination of the theoretical maximum resource efficiency of the system given the current structure (see section 5.4.1.1).

So, this chapter constitutes a complementary methodological development to the previous chapter since it provides a new set of indicators and relationships that capture and illustrate how the new sub-structural components identified in the previous chapter affect the environmental performance of the economic system.

Again, in this chapter, the term *disposals to nature* refers to all material flows that the economy releases back to the environment and it can be used interchangeably with the terms *waste* and *emissions*.

5.2 Linking the macroscopic and mesoscopic features of a system

5.2.1 The macroscopic and mesoscopic levels of observation of an IOT

Systems are characterised by the properties of their inner components — as an economy is characterised by all sectors composing it and how these sectors are related to each other. Thus, different levels of observation can be defined to assess the properties of either the system as a whole or of each of the system's subcomponents.

Each level of observation corresponds to a different system definition. The macroscopic observation corresponds to the observation of the system as a whole, i.e. the macro-economic behaviour when applied to the economic system. The microscopic observation deals with the most unitary components of the system, i.e. humans and companies in the case of the economic systems and its study is referred as micro-economics.

However, there is an intermediate level of observation — the mesoscopic level — that can be used to explain the macroscopic behaviour and can help understanding the link between microscopic and macroscopic phenomena. In economics, this level of observation corresponds to the sectoral approach, i.e. treating each sector as an independent system (although they are fundamentally composed of several microscopic elements, e.g. firms).

In this research, the mesoscopic level of observation (or mesoscopic structure) — i.e. how the sectors are related between them — is used to explain the macroscopic behaviour —

i.e. of the economy as a whole. The term macroscopic is hereafter shortened as the prefix "macro-" and, similarly, mesoscopic as "meso-".

Since the macro and meso levels of observation represent different systems, the indicators associated to each level of observation are, by definition, different: the efficiencies η used in all previous calculations are, in fact, meso-efficiencies, i.e. the efficiency of each sector as a single system (c.f. equation 4.54). A macro-efficiency — the resource efficiency of the system as a whole — also exists and is different from but related to the meso-efficiencies. How can both sets of indicators be calculated in a consistent manner?

IOTs relate the macro- and meso-structures of the economy by describing the economic system at the mesoscopic level of observation, revealing how sectors are related as independent systems. In other words, the IO framework provides disaggregated macroscopic measures matching its underlying mesoscopic structure. Thus, the meso-structure can be directly related to the macro-structure and, thus, be used to explain the macroscopic properties of the system. So, an IOT can be read either as the disaggregated measures of a single system representing the economy (c.f. top part of figure 5.1) or as the aggregated measures of n systems representing the n sectors of which the economy is composed (c.f. lower part of figure 5.1).

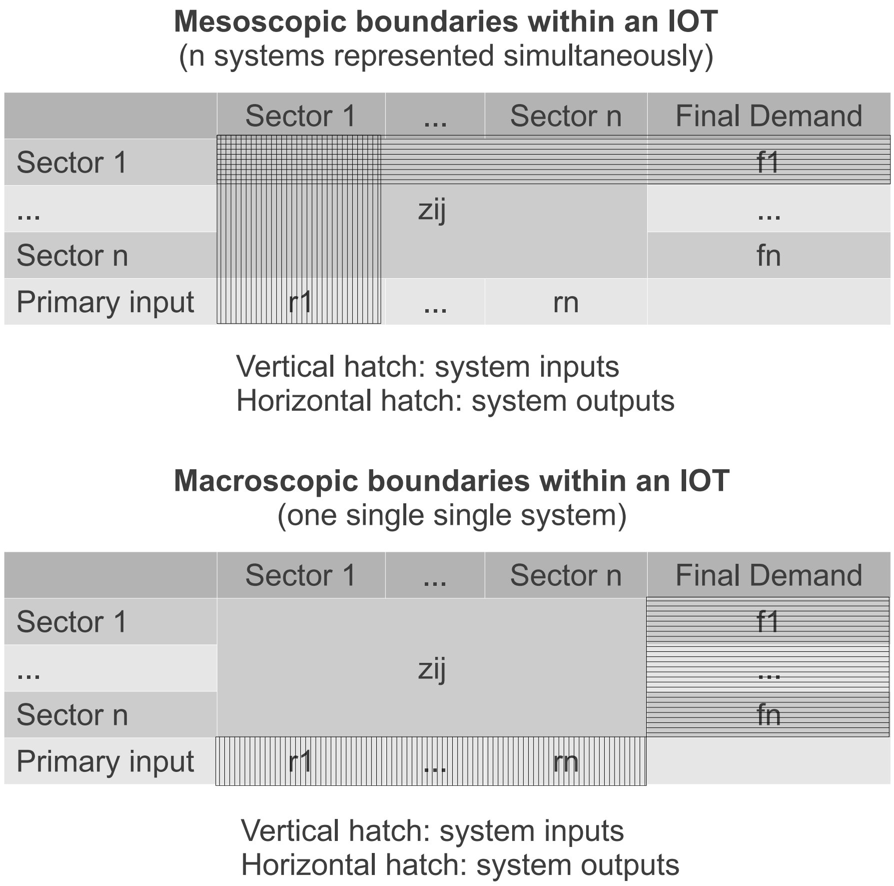

FIGURE 5.1: Macroscopic and mesoscopic boundaries within an IOT

Thus, an IOT enables extraction of indicators that are macroscopic — either aggregated or disaggregated — and mesoscopic — aggregated only. The mesoscopic indicators can only be disaggregated if a deeper level of observation is available. For instance, it is possible to disaggregate a mesoscopic measure by taking a microscopic perspective. However, representing three levels of observation with an IOT is not possible by definition, since the IOT represents a system and the linkage between its sub-components. Thus, only two levels of observation can coexist in a IOT, either macroscopic and mesoscopic (when representing the economy as a whole using sectors as the system subcomponents), or mesoscopic and microscopic (when representing a sector activity as the system and its sub-processes and system subcomponents). This research restricts its scope to the macroscopic–mesoscopic approach since the intent of the research is to explore the resources, outputs and emissions of entire economies, leaving the mesoscopic measures and indicators aggregated.

5.2.2 Application to the resource efficiency of the economy

This section recalls how to calculate sectoral efficiency, relates it to the meso-structure of the IOT and shows how to calculate the aggregated macroscopic resource efficiency of an economy by using disaggregated macroscopic measures.

The sectoral resource efficiency η_i defined in equation 4.54, hereafter meso-efficiency (short for mesoscopic resource efficiency), matches the elements in the top part of figure 5.1.

The macro-efficiency ${}^{macro}\eta$ (short for macroscopic resource efficiency) can be derived by observing the lower part of figure 5.1: the resource efficiency is the useful outputs divided by the total inputs; in the IOT case, this means all final goods divided by all primary resources.

$$^{macro}\eta = \frac{\sum_{i=1}^{n} f_i}{\sum_{i=1}^{n} r_i} \tag{5.1}$$

Although the macro-efficiency is based on aggregating disaggregated macroscopic measures (or indicators[1]) f_i and r_i, the relationship between the macroscopic property (the macro-efficiency) and the mesoscopic structure is not straight forward.

[1] In case of the product-based structures, the disaggregated measures of the resources required and emissions generated are structural indicators since they represent the intensities of use or generation of the production per unit of a specific good.

5.2.3 Mesoscopic intensities and mesoscopic resource efficiencies as shapers of the structure

In section 4.5, the production structure was decomposed into its meta-structural cyclic and acyclic components. But how do these meta-structures affect the properties of the system? And how are these meta-structures determined? In other words, what shapes the structure of a system?

These questions are central to this research. If they can be answered, there might be a way to identify which are the key structural components that have greater influence on the aggregate structure and, more importantly, to be able to modify the macroscopic properties of the system to improve overall performance of that system, by modifying these key structural components. Then, the environmental impact of economies, i.e. of human-induced material flows — emission generation and resource consumption — can be reduced systemically without modifying the amount of final goods produced.

The mesoscopic resource efficiencies constitute in fact an aggregate indicator of how each sector is related to the rest of the economy. They reveal how much each sector requires from the rest of the sectors (including primary resources) given a fixed production "recipe" (c.f. page 170). The production recipe is given by the production structure but it could be modified if there were indicators linking the different components of the production recipe to the level of activity. Such type of indicators are the *mesoscopic intensities*.

Each mesoscopic intensity — *meso-intensity* hereafter — represents how much a given sector requires from another sector to produce one unit of goods, i.e. they indicate how sectors are related to each other. For example, how much wood or metals are required by the manufacturing industry or how much processed food is required by the food services industry. They can be defined as follows: for a sector j of a PIOT with n sectors and m resource rows, each sector has $n + m$ meso-intensities:

$$y_{ij} = \frac{z_{ij}}{\underline{x}_j - w_j} \tag{5.2}$$

and, in the case of resource q

$$y_{qj} = \frac{r_{qj}}{\underline{x}_j - w_j} \tag{5.3}$$

The meso-intensities of a given sector are related to the mesoscopic resource efficiency of that sector: the inverse of the meso-intensities' sum equals the meso-efficiency of that sector.

$$\eta_j = \frac{1}{\sum_{i=1}^{n+m} y_{ij}} \tag{5.4}$$

The corollary of equation 5.4 is that reducing a single meso-intensity increases the meso-efficiency, while increasing the meso-efficiency implies reducing all meso-intensities given the production recipe of that sector. Thus, the practical consequence for material flow management is that environmental and industrial policies should target meso-intensities rather than meso-efficiencies, because the meso-efficiencies are determined by the meso-intensities. In other words, the mesoscopic resources efficiencies and the production recipes are explained by the different meso-intensities, since altering a meso-intensity implies altering the production recipe and associated meso-efficiency. So, meso-intensities constitute the most disaggregated level of indicators and their modification alters the structure of the system. Thus, meso-intensities constitute the ultimate determinant of the system structure.

However, meso-intensities on their own are not useful to identify how the system is linked as a whole since they only relate sectors two by two (a meso-intensity indicates how much a given sector requires from the other sectors to produce its own goods). In other words, they are not helpful to trace systemic impacts. Thus, a different approach needs to be used to assess the systemic impacts derived from modifying the meso-intensities. In this sense, the meta-structural decomposition developed in section 4.5 can be used for that purpose because it constitutes the link between the macroscopic properties of the system and the meso-intensities. The meta-structures reveal how the physical structure of the economic system can be decomposed into smaller units conveying how systemic effects spread. By analysing the meta-structures, key meso-intensities affecting the overall system performance can then be identified. Finally, policies can be devised to alter the meso-intensities in an informed manner to induce the desired changes in the structure.

Policies can be industrial, e.g. to improve the resource efficiency of the economic system vis-à-vis selected resources to reduce the degree of (international or national) resource dependency, or environmental, e.g. to lower the generation of certain emissions. In both cases, key meso-intensities act as red flags where policy-makers should focus on, since they are a proxy for the technology currently used and its impacts. For instance, if a given meso-intensity, e.g. y_{12} corresponding to the intersectoral flow z_{12}, is too high and induces great emissions and systemic effects, then policy makers will have to investigate what is the underlying technology used by sector 2 to transform goods from sector 1 and then suggest regulation or other incentives to lower the meso-intensity by changing or adapting the transformation technology.

5.3 Developing structural indicators

5.3.1 Capturing systemic interactions

In section 4.5, the cyclic–acyclic and the direct–indirect meta-structures have been identified and associated to specific functions of the system. The question is now which structural components induce most emissions or resource extraction, and to be able to use this knowledge to mitigate these effects, i.e. to reduce the environmental impact of the economy.

According to section 5.2, meso-intensities are the ultimate structural determinant. So, this section aims to develop structural indicators to identify the structural components inducing systemic interaction so that key meso-intensities within these structures could be targeted to mitigate emission generation and resource consumption systemically for the aggregated economy.

The cyclic–acyclic meta-structure reveals which flows are associated to the maintenance (cyclic) structure or to the productive (acyclic) structure (c.f. section 4.5.1.1). The cyclic structure links, by definition, the different sectors of the economy by cyclic connections and is thus a main container of systemic interactions. The indirect component of the direct–indirect meta-structure is also a key component to analyse since it reveals the cascaded reallocation of resources (c.f. section 4.5.1.2), which generates more losses than if resources were used directly. Thus, it is also a key structure to monitor since it might allow for the reduction of specific emissions or resources indirectly.

In this section, an indicator framework is developed to quantify the amount of flows associated to the cyclic component of the cyclic–acyclic meta-structure and to the indirect component of the direct–indirect meta-structure, because both components are key to identify (and thus reduce) systemic flows. Four indicator types are developed below for the cyclic and indirect meta-structures, capturing correspondingly:

1. the predominant type of meta-structure (i.e. the weight of the sub-structure over the meta-structure);
2. the systemic linkage of the meta-structure;
3. the systemic environmental impact[2] of the meta-structure (i.e. how many emissions are generated (or resources consumed) by that sub-structure);
4. the total weight of the meta-structure on the system (i.e. the total flows related to that sub-structure).

[2]The emissions generated and resources used by the system are used as a proxy for the environmental impact of the economy. In more sophisticated IO frameworks, these can be directly related to specific environmental impacts.

Indicators 1, 3, and 4 are first presented in an intensity form, i.e. per unit of final good produced, indicated by the *Iy*-ending. Then, two indexed forms are also developed: a relative index, indicated by the *RIx*-ending, normalised by the relevant sub-structural component (e.g. only inter-sectoral flows); and an absolute index, indicated by the *AIx*-ending, normalised by the total flows of the structure so that a common denominator exists to compare the three indicators. Note that the absolute and relative index of the fourth indicator are the same since the relevant structure is the whole structure.

Indicators 1, 2, and 3 allow for the full characterisation of the systemic effects. For example, focussing on the cyclic structure: the three indicators are required since a high amount of cycling (indicator 1) does not necessarily imply a high amount of cycling emissions (indicator 3); and a high amount of cycling emissions (indicator 3) does not imply a high amount of cycling throughput (indicator 1). Indicator 2 explains the systemic relationship between indicator 1 and 3. The higher indicator 2 is, the more the emissions are systemically generated (e.g. generated by inter-sectoral cycling rather than cycling within the same sector). Indicator 4 is a comprehensive index merging the information provided by the previous indicators but cannot substitute them when a detailed structural analysis is sought.

A detailed structural analysis can be performed by studying the indicators in the order provided. The first indicator set reveals whether much cycling or indirect flows exist. The second indicator reveals whether these flows induce systemic effects. The third indicator reveals the impact of these flows on the system. The fourth indicator is a compact indicator merging the information of the first and third indicator, so it can be used for comparative purposes or rapid assessment of the relevance of the sub-structure under study.

The indicators are calculated for each product-based structure (denoted by the s_p superscript) but can also be applied directly to the cyclic and indirect meta-structures of the original PIOT.

5.3.2 Indicators related to the cyclic structure

The indicators developed in this section can be applied to assess both the effects of pre-consumer and post-consumer cycling. In case where both types of cycling exist, the indicators could be calculated for the total cyclic structure or for each type of cycling. The illustrative example developed in chapter 6 only traces pre-consumer cycling, so the indicators will only capture the systemic effects of pre-consumer cycling.

5.3.2.1 Indicators quantifying intersectoral cycling

Cycling Intensity (CIy) The cyclic flows are fundamentally characterised by the cyclic matrix $\mathbf{Z}^c$ (c.f. section 4.2). Intuitively, calculating the Cycling Intensity (CIy) indicator just requires adding all these flows to reveal the amount of cycling happening within the product-based structures per unit of final good, as follows

$$ {}^{s_p}CIy = \sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}^{c} \tag{5.5}$$

So, the cycling intensity indicator is between zero (included when there is no cycling) and infinity (higher numbers meaning higher amount of cycling).

Cycling Relative Index (CRIx) The Cycling Relative Index (CRIx) relates the amount of cycling (which happens as part of the inter-sectoral flows) to the total amount of intersectoral flows, as follows:

$$ {}^{s_p}CRIx = \frac{{}^{s_p}CIy}{\sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}} \tag{5.6}$$

So, the CRIx is between zero (included when there is no cycling) and one when all intersectoral flows are cyclic (included and implying there are no indirect flows).

Cycling Absolute Index (CAIx) The Cycling Absolute Index (CAIx) relates the amount of cycling to the total throughput of the system to reveal the relative weight of cycling in the system, as the Cycling Index of Finn (1976) aimed to capture.

$$ {}^{s_p}CAIx = \frac{{}^{s_p}CIy}{\sum_{i=1}^{n} {}^{s_p}\underline{x}_i} \tag{5.7}$$

So, the CAIx index is between zero (included when there is no cycling) and one (not included[3]) and indicating that not only the inter-sectoral flows are dominated by cycling but also that the total system flows are dominated by the inter-sectoral ones; so, there is not many final outputs generated either as final goods or emissions.

[3] One is not included because it is assumed that the meso-efficiencies cannot equal one. If they were and in the case where the system has no acyclic flows, all cyclic ones would be confined within the system, without emissions nor primary resources required — that would be the only case where intersectoral cycling would equal the system throughput.

5.3.2.2 Indicator quantifying the systemic linkage of the cyclic sub-structure

Since not all cycles are inter-sectoral — some can happen within the same sector —, the degree of systemic linkage induced by the cyclic structure is not straight forward. The proportion of inter-sectoral cycling flows must be distinguished from the cycling flows happening within the same sector. In section 4.6.1, the Cyclic Connectivity indicator was developed for that purpose. However, it accounted for the cycling connectivity of a given sector (c.f. equation 4.87), i.e. that indicator corresponds to the mesoscopic Cyclic Connectivity. The macroscopic Cyclic Connectivity (${}^{macro}CC$) is defined using the same rationale to reveal the total amount of inter-sectoral cycling over total cycling, as follows:

$$
{}^{macro}CC = \frac{\sum_{i=1}^{n} c_i^{inter}}{\sum_{i=1}^{n}\sum_{j=1}^{n} z_{ij}^{c}} \tag{5.8}
$$

5.3.2.3 Indicators quantifying the environmental impact of cycling

The previous indicators reveal the structure of the system, but not its environmental consequences. The indicators of this section aim to convey that latter aspect by using the emissions, since the type and amount of emissions are due to the arrangement of the structure and it is the type and amount of emissions that determine the environmental impact of the economic system. In this sense, emissions can be used as a proxy for the environmental impact. To capture the whole effect of cycling, both the direct and indirect cycling emissions are included: the use of the *-superscript denotes all cycle-related flows.

Cycling Emissions Intensity (CEIy) Thus, the Cycling Emissions Intensity (CEIy) can be defined as follows,

$$
{}^{s_p}CLIy = \sum_{i=1}^{n} {}^{s_p}w_i^{*c} \tag{5.9}
$$

So, the $CLIy$ is between zero (included when there are no cycling emissions) and infinity (higher numbers meaning higher amount of cycling emissions).

Cycling Emissions Relative Index (CERIx) The Cycling Emissions Relative Index (CERIx) relates the emissions from the cyclic structure to the total emissions,

$$
{}^{s_p}CERIx = \frac{{}^{s_p}CLIy}{\sum_{i=1}^{n} {}^{s_p}w_i} \tag{5.10}
$$

So, the CERIx is between zero (included) — indicating there are no emissions derived from cycling — and one (included, indicating that all emissions are due to the indirect components and implying that there is no direct component).

Thus, the CERIx does not quantify how much cycling is happening but how this cycling is affecting the dissipative system; in other words, it does not quantify the level of cycling but the effect of cycling on the amount of emissions generated. This indicator is important because few cycling can generate many emissions or vice-versa, depending on the mesoscopic efficiencies.

Cycling Emissions Absolute Index (CEAIx) The Cycling Losses Absolute Index (CEAIx) relates the emissions from the cyclic structure to the total outputs,

$$^{s_p}CEAIx = \frac{^{s_p}CLIy}{\sum_{i=1}^{n} {^{s_p}\underline{x}_i}} \tag{5.11}$$

So, the CEAIx is between zero (included) — indicating there are no emissions derived from cycling — and one (not included) — indicating that the emissions represent much of the system's flows and they are dominated by cycling losses.

5.3.2.4 Indicators quantifying the total weight of the cyclic structure

The idea behind the comprehensive indicator is to provide information on the amount of cycling happening within the system and how this cycling is affecting the whole system at the same time, i.e. combining the former indicators. The *-superscript denotes the whole intersectoral flows and emissions associated to cycling.

Comprehensive Cycling Intensity (CCIy) The Comprehensive Cycling Intensity (CCIy) is defined as follows:

$$^{s_p}CCIx = \sum_{i=1}^{n}\sum_{i=j}^{n} {^{s_p}z_{ij}^{*c}} + \sum_{i=1}^{n} {^{s_p}w_i^{*c}} \tag{5.12}$$

So, the CCIy is between zero (included) — indicating there is no cycling — and one (included in the case there is no acyclic flows) — indicating that much of the inter-sectoral and final flows are dominated by cycling.

Comprehensive Cycling Index (CCIx) In this case, there is no difference between the relative and absolute index since the relevant normalising structure is total outputs. The Comprehensive Cycling Index (CCIx) relates all flows induced by cyclic structure to the total outputs of the structure:

$$^{s_p}CCIx = \frac{^{s_p}CCIy}{\sum_{i=1}^{n} {^{s_p}\underline{x}_i}} \tag{5.13}$$

So, the CCIx is between zero (included) — indicating there is no cycling — and one (included in the case there is no acyclic flows) — indicating that much of the inter-sectoral and final flows are dominated by cycling.

The $CCIx$ represents an intuitive and quick indicator to have an overview of the effect of cycling on the system (0 means no cycling and 1 means all flows belong to cycling). However, this indicator masks whether the dominance of cycling is either due to its inter-sectoral component ($\mathbf{Z}^c$) or to its associated system effects (i.e. the emissions associated to cycling, so it cannot be used when a detailed structural analysis is sought).

5.3.3 Indicators related to the indirect structure

5.3.3.1 Indicators quantifying the indirect intersectoral structure

This indicator set is based on $\mathbf{Z}^{ind}$ which reveals how the inputs of each sector are allocated to the other sectors; thus, each row sum of $\mathbf{Z}^{ind}$ corresponds to the total amount of resources passed to another sector — i.e. reallocated — instead of being transformed into a final good. Consequently, the total sum of $\mathbf{Z}^{ind}$ represents the total flows reallocated within the system.

Reallocation Intensity (RIy) The Reallocation Intensity (RIy) indicator reveals the amount of flows reallocated per unit of final goods, as follows:

$$ {}^{s_p}RIy = \sum_{i=1}^{n} \sum_{j=1}^{n} {}^{s_p}z_{ij}^{*ind} \tag{5.14} $$

So, the RIy ranges from zero (included when no indirect structure is present) to infinity (higher numbers indicate more reallocated flows).

Reallocation Relative Index (RRIx) The Reallocation Relative Index (RRIx) relates the weight of the indirect intersectoral flows to the total intersectoral flows,

$$ {}^{s_p}RRIx = \frac{{}^{s_p}RRIy}{\sum_{i=1}^{n} \sum_{j=1}^{n} {}^{s_p}z_{ij}} \tag{5.15} $$

So, the RRIx ranges from zero (included when no indirect structure is present) to one (meaning that intersectoral flows belong to the indirect structure).

Reallocation Absolute Index (RAIx) The Reallocation Absolute Index (RAIx) relates the weight of the indirect intersectoral flows to the total outputs,

$$ {}^{s_p}RAIx = \frac{{}^{s_p}RIy}{\sum_{i=1}^{n} {}^{s_p}\underline{x}_i} \tag{5.16} $$

So, the RAIx ranges from zero (included when no indirect structure is present) to one (meaning that all primary resources have been reallocated to other sectors, although one cannot be reached due to the emissions which happen in the same sector where the primary resources are consumed).

5.3.3.2 Indicator quantifying the systemic linkage of the indirect sub-structure

This indicator aims to capture the reallocation degree compared to the original flows going through the system (instead of normalising them by the same inter-sectoral structure where the indirect flows are counted, as in the previous indicators' case). Thus, the Reallocation Index (RIx) uses total final outputs as the normalising unit (which are the same as total primary inputs). In other words, it indicates the amount of reallocation happening as a fraction on the final outputs.

$$ {}^{s_p}RIx = \frac{{}^{s_p}RIy}{\sum_{i=1}^{n} {}^{s_p}f_i + {}^{s_p}w_i} \tag{5.17} $$

So, the RIx ranges from zero (included when no reallocation happens) to infinite (when the amount of reallocated flows exceeds the amount of final outputs).

5.3.3.3 Indicators quantifying the environmental impact of the indirect structure

Similarly to the cycling indicators, the environmental impact of the indirect structure is measured by the emissions the indirect structure generates, since the type and amount of emissions are the consequence of the indirect structure and the emissions are the material flows that determine the environmental impact of the economies (therefore, they can be used as a proxy for the environmental impact).

Reallocation Emissions Intensity (REIy) The emissions per unit of final good due to the cycling structures are captured by the Reallocation Emissions Intensity (REIy). The *-superscript denotes *all* indirectly induced emissions.

$$ {}^{s_p}REIy = \sum_{i=1}^{n} {}^{s_p}w_i^{*i} \tag{5.18} $$

So, the REIy ranges from zero (included when no indirect structure is present) to infinity (higher numbers indicate higher indirect emissions).

Reallocation Emissions Relative Index (RERIx) The Reallocation Emissions Relative Index (RERIx) relates the emission due to the indirect structure to the total emissions, as follows:

$$ {}^{s_p}RERIx = \frac{{}^{s_p}REIy}{\sum_{i=1}^{n} {}^{s_p}w_i} \tag{5.19} $$

So, the RERIx ranges from zero (included when no indirect structure is present) to one (meaning that all emissions are due to the indirect structure).

Reallocation Emissions Absolute Index (REAIx) The Reallocation Emissions Absolute Index (REAIx) relates the emission due to the indirect structure to the total outputs, as follows:

$$ {}^{s_p}REAIx = \frac{{}^{s_p}REIy}{\sum_{i=1}^{n} {}^{s_p}\underline{x}_i} \tag{5.20} $$

So, the REAIx ranges from zero (included when no indirect structure is present) to one (meaning that the indirect emissions dominate the system flows).

5.3.3.4 Indicators quantifying the total weight of the indirect structure

Comprehensive Reallocation Intensity (CRIy) The Comprehensive Reallocation Intensity (CRIy) traces all flows induced by the indirect structure per unit of final good, as follows:

$$ {}^{s_p}CRIy = \sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}^{*i} + \sum_{i=1}^{n} {}^{s_p}f_i^{ind} + \sum_{i=1}^{n} {}^{s_p}w_i^{*i} \tag{5.21} $$

So, the CRIy ranges from zero (included when no indirect structure is present) to infinity (higher numbers indicate higher indirect flows).

Comprehensive Reallocation Index (CRIx) The Comprehensive Reallocation Index (CRIx) reveals the weight of all flows induced by the indirect structures on the total structure. Since the relevant structure is the total outputs, there is no difference between the relative and absolute indicators.

$$ {}^{s_p}CRIx = \frac{{}^{s_p}CRIy}{\sum_{i=1}^{n} {}^{s_p}\underline{x}_i} \tag{5.22} $$

So, the CRIx ranges from zero (included when no indirect structure is present) to one (when there is no direct structure and no cycling).

5.3.4 Relating the macroscopic resource efficiency and indicators to their product-based counterparts

In this section, the macroscopic resource efficiency and indicators of the original structure are related to their product-based counterparts, using the linear relationship between the original structure and product-based structures (c.f equation 4.17). This relationship is key for the structural analysis of the PIOT since it allows for the determination of the relative and absolute contribution of each product-based structure to the original structure.

5.3.4.1 Relating the macroscopic efficiency of the economic system to the product-based macroscopic efficiencies

The product-based decomposition reveals the different structures underlying the production of each final good, each having its own specific macro-properties. Despite stemming from the same Leontief inverse matrix, each product-based structure has its particular inter-sectoral relationships with specific, differentiated cyclic–acyclic and direct–indirect meta-structures; thus, each product-based structure has its specific macro-efficiency. So, despite sharing the same mesoscopic properties across all its subcomponents, i.e. each sector has its own specific meso-efficiency and production "recipe" (which are the same in all product-based structures), and despite sharing the same initial structure, each product-based structure has its own specific macroscopic properties.

Recalling the notation of the product-based structures (c.f. table 4.8), the macro-efficiency (defined as in equation 5.1) of a product-based structure is

$$^{s_p,macro}\eta = \frac{\sum_{i=1}^{n} {}^{s_p}u_i}{\sum_{i=1}^{n} {}^{s_p}r_i} \tag{5.23}$$

Developing equation 5.1 using equations 4.12, 4.16, 5.23 and the commutative property of summation:

$$\begin{aligned} ^{agg,macro}\eta &= \frac{\sum_{i=1}^{n} {}^{agg}f_i}{\sum_{i=1}^{n} {}^{agg}r_i} \\ &= \frac{\sum_{i=1}^{n}\sum_{p=1}^{n} f_p \cdot {}^{s_p}u_i}{\sum_{i=1}^{n}\sum_{p=1}^{n} f_p \cdot {}^{s_p}r_i} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n} {}^{s_p}u_i}{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n} {}^{s_p}r_i} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p,macro}\eta}{\sum_{p=1}^{n} f_p} \end{aligned} \tag{5.24}$$

Thus, the macro-efficiency of the economic system is the average of the product-based macro-efficiencies weighted by the final demand of the corresponding product (c.f. equation 5.24). This relationship is a key analytical tool since it relates the resource efficiency of the aggregated structure of the economy to the productive structures of each final good, enabling identification of which product-based structure has the most influence in the macro-efficiency of the whole economy.

5.3.4.2 Relating the cycling indicators of the economic system to the product-based cycling indicators

An intensity indicator of the structure of the economic system can also be found as the linear combination of intensity indicators of the product-based structures. For example, the cycling intensity indicator (CIy) of the original structure (c.f. equation 5.5) can be decomposed using the linear relationship between the original structure and the product-based structures (c.f. equation 4.17). However, since it is an intensity, it must also be normalised by the total amount of goods produced (CIy, CEIy and CCIy are in fact normalised by 1).

$$
\begin{aligned}
{}^{agg}CIy &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} {}^{agg}z_{ij}^{c}}{\sum_{p=1}^{n} f_p} \\
&= \frac{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}^{c}}{\sum_{p=1}^{n} f_p} \\
&= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CIy}{\sum_{p=1}^{n} f_p}
\end{aligned} \tag{5.25}
$$

The same decomposition can be applied to the Cyclic Emissions Intensity (CEIy) and Comprehensive Cycling Intensity (CCIy):

$$
{}^{agg}CEIy = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CEIy}{\sum_{p=1}^{n} f_p} \tag{5.26}
$$

$$
{}^{agg}CCIy = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CCIy}{\sum_{p=1}^{n} f_p} \tag{5.27}
$$

The relative and absolute index indicators of the original structure are also given by the average of their product-based counterpart, weighted by the final production of each product-based structure. For example, the cycling relative index (CRIx) of the original structure (c.f. equation 5.6) can be decomposed using the linear relationship between the original structure and the product-based structures (c.f. equation 4.17), as follows:

$$\begin{aligned} {}^{agg}CRIx &= \frac{{}^{agg}CIy}{\sum_{i=1}^{n}\sum_{j=1}^{n} {}^{agg}z_{ij}} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CIy}{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CRIx}{\sum_{p=1}^{n} f_p} \end{aligned} \tag{5.28}$$

The same reasoning can be applied to the rest of the relative and absolute indexed indicators since they are all normalised by structural components. Thus,

$${}^{agg}CAIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CAIx}{\sum_{p=1}^{n} f_p} \tag{5.29}$$

$${}^{agg}CERIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CERIx}{\sum_{p=1}^{n} f_p} \tag{5.30}$$

$${}^{agg}CEAIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CEAIx}{\sum_{p=1}^{n} f_p} \tag{5.31}$$

$${}^{agg}CCIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CCIx}{\sum_{p=1}^{n} f_p} \tag{5.32}$$

The Cyclic Connectivity of the original structure is also a weighted average of the product-based structures:

$$\begin{aligned} {}^{agg}CC &= \frac{\sum_{i=1}^{n} {}^{agg}c_i^{inter}}{\sum_{i=1}^{n}\sum_{j=1}^{n} {}^{agg}z_{ij}^{c}} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n} {}^{s_p}c_i^{inter}}{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} {}^{s_p}z_{ij}^{c}} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CC}{\sum_{p=1}^{n} f_p} \end{aligned} \tag{5.33}$$

5.3.4.3 Relating the indirect indicators of the economic system to the product-based indirect indicators

Following the rationale and demonstrations of the previous section, the intensity indicators related to the indirect meta-structure of the original structure are the linear combination of the intensity indicators of the product-based structures weighted by the final production of each product-based structure:

$$ {}^{agg}RIy = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}RIy}{\sum_{p=1}^{n} f_p} \tag{5.34} $$

$$ {}^{agg}REIy = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}REIy}{\sum_{p=1}^{n} f_p} \tag{5.35} $$

$$ {}^{agg}CRIy = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CRIy}{\sum_{p=1}^{n} f_p} \tag{5.36} $$

Following the rationale and demonstrations of the previous section, the relative and absolute index indicators of the original structure are given by the average of their product-based counterpart, weighted by the final production of each product-based structure, as follows:

$$ {}^{agg}RRIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}RRIx}{\sum_{p=1}^{n} f_p} \tag{5.37} $$

$$ {}^{agg}RAIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}RAIx}{\sum_{p=1}^{n} f_p} \tag{5.38} $$

$$ {}^{agg}RERIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}RERIx}{\sum_{p=1}^{n} f_p} \tag{5.39} $$

$$ {}^{agg}REAIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}REAIx}{\sum_{p=1}^{n} f_p} \tag{5.40} $$

$$ {}^{agg}CRIx = \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}CRIx}{\sum_{p=1}^{n} f_p} \tag{5.41} $$

The Reallocation Index (RIx) of the original structure is also a weighted average of the product-based structures:

$$ \begin{aligned} {}^{agg}RIx &= \frac{{}^{agg}IIy}{\sum_{i=1}^{n}({}^{agg}f_i + {}^{agg}w_i)} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}IIy}{\sum_{p=1}^{n} f_p \cdot \sum_{i=1}^{n}({}^{s_p}f_i + {}^{s_p}w_i)} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p}RIx}{\sum_{p=1}^{n} f_p} \end{aligned} \tag{5.42} $$

5.4 Relating the macroscopic resource efficiency and emissions to the product-based structures, meta-structures and mesoscopic resource efficiencies

The aim of this section is to show the relationship between the different meta-structures and the properties of the system (e.g. the macroscopic resource efficiency of the system). This is key because it constitutes a structural relationship that implies that the properties of the system can be altered by modifying its meta-structures. In particular, it helps in determining the maximal resource efficiency of the economy given the available meta-structures. This is thus an important tool to identify the relevant structures to be targeted when aiming to mitigate the emissions or resource consumption of an economy.

The relationships developed in this section focus on the structural components of a traditional PIOT. Thus, the structural relationships involving cycling apply exclusively to pre-consumer cycling. It is thus expected to find the analytical demonstration of the counter-intuitive systemic effects of pre-consumer cycling revealed in section 4.4 (i.e., that pre-consumer cycling reduces the macroscopic resource efficiency of the economy).

5.4.1 Relating the macroscopic efficiency of a given system to its meta-structures and mesoscopic resource efficiencies

The cyclic–acyclic and direct–indirect meta-structures constitute a relevant division of the macroscopic structure at mesoscopic level and can thus be considered as structural features characterising the relationship between the macroscopic and mesoscopic systems. This is relevant because each mesoscopic structure entails specific properties that affect the macroscopic behaviour; in particular, because the meso-structures stem from the inter-sectoral relationships and it is only after connecting the different sectors in a specific manner that the macroscopic properties arise. Thus, the macro-efficiency from equation 5.1 can be decomposed into the meta-structures or properties (e.g. the cycling throughput or meso-efficiencies), to find the relationship between the macro-efficiency and the underlying mesoscopic and structural properties.

Using equations 4.79, 4.80 and 4.58 to decompose the final demand,

$$\mathbf{f}' = \mathbf{f}^{dir'} + \mathbf{f}^{ind'} \tag{5.43}$$

$$= \mathbf{r}^{a,dir'} \cdot \hat{\boldsymbol{\eta}} + \mathbf{i}' \cdot \mathbf{Z}^{ind,ac,a} \cdot \hat{\boldsymbol{\eta}} \tag{5.44}$$

or

$$= \mathbf{r}^{a,dir'} \cdot \hat{\boldsymbol{\eta}} + \mathbf{i}' \cdot (\mathbf{Z} - \mathbf{Z}^{c} - \mathbf{Z}^{ind,c} - \mathbf{Z}^{ind,ac,c}) \cdot \hat{\boldsymbol{\eta}} \tag{5.45}$$

Equations 5.44 and 5.45 reveal the relationship between the structure of the system and its final production. In particular, equation 5.44 shows that the final goods production depends on the acyclic–direct and acyclic–indirect structures (which is intuitive since, by definition, it is the acyclic structure that transforms the primary resources into final goods). However, equation 5.45 reveals the implicit complementary relationship between the cyclic and acyclic structures: the less cycling happens within the system (i.e. the smaller the intersectoral components $\mathbf{Z}^{c}$, $\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac,c}$ are), the more final goods are produced given the same level of intersectoral flows $\mathbf{Z}$. Thus, both the cyclic and acyclic components affect the system's' ability to produce final goods and affect consequently its macro-efficiency.

Using equations 5.44, 5.45 and 4.78 in 5.1, the general definition of ${}^{macro}\eta$ becomes

$$ {}^{macro}\eta = (\mathbf{r}^{a,dir'} + \mathbf{i}' \cdot \mathbf{Z}^{ind,ac,a}) \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot (\mathbf{i}' \cdot (\mathbf{r}^{a,dir} + \mathbf{r}^{c,dir} + \mathbf{r}^{ind,ac,a} + \mathbf{r}^{ind,ac,c}))^{-1} \quad (5.46) $$

or, alternatively,

$$ {}^{macro}\eta = \left[\mathbf{r}^{a,dir'} + \mathbf{i}' \cdot (\mathbf{Z} - \mathbf{Z}^{c} - \mathbf{Z}^{ind,c} - \mathbf{Z}^{ind,ac,c})\right] \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot \\ (\mathbf{i}' \cdot (\mathbf{r}^{a,dir} + \mathbf{r}^{c,dir} + \mathbf{r}^{ind,ac,a} + \mathbf{r}^{ind,ac,c}))^{-1} \quad (5.47) $$

Equations 5.46 and 5.47 are key because they relate the macro-efficiency of the whole system to the mesoscopic properties of each sector (i.e. the meso-efficiencies) and to how the different sectors are interlinked (i.e. to its meta-structural components). A key finding is that having a lower pre-consumer cyclic component ($\mathbf{Z}^{c}$ and associated flows $\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac,c}$) leads to a higher macro-efficiency since the primary resources associated to cycling ($\mathbf{r}^{c,dir}$ and $\mathbf{r}^{ind,ac,c}$) will be lower, increasing the macro-efficiency (given the same level of final demand). This finding constitutes the analytical demonstration of the findings of section 4.4.4, where the systemic effects of pre-consumer cycling were found to reduce the resource efficiency of the system.

5.4.1.1 Special structural cases and maximal macro-efficiencies

Equations 5.46 and 5.47 can be narrowed for specific structural cases.

No cyclic meta-structure For example, in the case where there is no cycling but the same amount of final goods are produced (i.e. only the acyclic–direct and acyclic–indirect structures are present),

$$ \mathbf{Z}^{ind,ac,a} = \mathbf{Z} \quad (5.48) $$

Then, equation 5.46 becomes

$$^{macro}\eta = (\mathbf{r}^{a,dir'} + \mathbf{i}' \cdot \mathbf{Z}) \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot (\mathbf{i}' \cdot (\mathbf{r}^{a,dir} + \mathbf{r}^{ind,ac,a}))^{-1} \tag{5.49}$$

proving that, for the same amount of final goods produced, a structure without cycling is more resource efficient: the resource efficiency in equation 5.49 is higher than the one in equation 5.46 due to the smaller amount of resources required: $\mathbf{r}^{ind,ac,a}$ and $\mathbf{r}^{c,dir}$ are missing since there is no cycling.

Also, the macro-efficiency in equation 5.49 corresponds to the maximal efficiency of the system without pre-consumer cycling. Although it might not be possible to avoid completely pre-consumer cycling, this equation provides a theoretical upper limit to the macro-efficiency given the acyclic–indirect structure.

Neither cyclic nor indirect meta-structures In the case where there is neither cycling nor indirect flows, only the acyclic–direct structures is present; so,

$$\mathbf{Z} = 0 \text{ and } \mathbf{r}^{a,dir} = \mathbf{r} \tag{5.50}$$

Then,equation 5.46 becomes

$$\begin{aligned} ^{macro}\eta &= \mathbf{r} \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot (\mathbf{r}' \cdot \mathbf{i})^{-1} \\ &= \frac{\sum_{i=1}^{n} (r_i \cdot \eta_i)}{\sum_{i=1}^{n} r_i} \end{aligned} \tag{5.51}$$

In equation 5.51, the macro-efficiency is not related to any intersectoral sub-structure, since the acyclic–direct structure has no inter-sectoral component by definition. In this particular case, since there are not intersectoral interactions, the macro-efficiency becomes the average of the meso-efficiencies weighted by the amount of primary resources used by each sector. Although it is impossible to avoid the acyclic–indirect structure completely since final goods require intermediate goods of different degrees of fabrication (i.e requiring the acyclic–indirect structure), this equation provides a theoretical absolute upper limit to the macro-efficiency for the acyclic–direct structure.

This equation also proves that the acyclic–indirect structure contributes to lower the macro-efficiency of a system, since in order to produce the same amount of final goods, less primary resources are required.

5.4.2 Relating the macroscopic efficiency of the economic system to the product-based meta-structures and meso-efficiencies

Section 5.4.1 revealed that the macro-efficiency of a given structure is related to its own meta-structures and the meso-efficiencies of its sub-systems. Since the macro-efficiency of the whole economy is also related to the product-based macro-efficiencies (c.f. equation 5.24), the macro-efficiency of the whole economy is ultimately a function of the product-based meta-structures and meso-efficiencies, as follows

$$\begin{aligned} {}^{agg,macro}\eta &= \frac{\sum_{p=1}^{n} f_p \cdot {}^{s_p,macro}\eta}{\sum_{p=1}^{n} f_p} \\ &= \frac{\sum_{p=1}^{n} f_p \cdot \left[\left({}^{s_p}\mathbf{r}^{a,dir'} + \mathbf{i}' \cdot {}^{s_p}\mathbf{Z}^{ind,ac,a} \right) \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot \left({}^{s_p}\mathbf{r}' \cdot \mathbf{i} \right)^{-1} \right]}{\sum_{p=1}^{n} f_p} \end{aligned} \tag{5.52}$$

5.4.3 Relating the macroscopic efficiency of the economic system to its meta-structures and meso-efficiencies

The macro-efficiency of the whole economy can be related to its own sub-structures by applying equation 4.17 to each product-based component of equation 5.52, as follows:

$${}^{agg,macro}\eta = \left({}^{agg}\mathbf{r}^{a,dir'} + \mathbf{i}' \cdot {}^{agg}\mathbf{Z}^{ind,ac,a} \right) \cdot \hat{\boldsymbol{\eta}} \cdot \mathbf{i} \cdot \left({}^{agg}\mathbf{r}' \cdot \mathbf{i} \right)^{-1} \tag{5.53}$$

5.4.4 Relating the emissions of the economic system to its meta-structures and the mesoscopic efficiencies

Finally, the relationship between the macroscopic emissions and the meta-structures and meso-efficiencies is analysed. It constitutes a complementary approach to the study of the resource efficiency since the emissions are a direct consequence of the specific resource efficiency of a system. However, there might be times where the analysis of the drivers of specific emissions is the focus of interest and thus, studying the direct relationship between the emissions and the structure is preferable.

To start with, the total emissions are disaggregated between the emissions of each sub-structure; then, these are related to more specific components, finding that despite the large amount of different inter-sectoral relationships, the emissions of the whole system are defined by five different structural parameters: $\mathbf{c}^{dir}$, $\mathbf{c}^{ind}$, $\mathbf{Z}^{ind,ac}$, $\boldsymbol{\eta}$ and $\mathbf{r}$.

From tables 4.21, 4.22, 4.23 and 4.24,

$$w_j = w_j^{ind,c} + w_j^{ind,ac,c} + w_j^{c,dir} + w_j^{ind,ac,a} + w_j^{a,dir} \tag{5.54}$$

$$r_j = r_j^{ind,ac,c} + r_j^{c,dir} + r_j^{ind,ac,a} + r_j^{a,dir} \tag{5.55}$$

Substituting equations 4.25[4], 4.71, 4.72, 4.73 and 4.82 in equation 5.54,

$$w_j = \frac{c_j^{ind} \cdot (1-\eta_j)}{\eta_j} + \left(\sum_{i=1}^{n} z_{ij}^{ind,ac,c} + r_j^{ind,ac,c} \right) \cdot (1-\eta_j) + \frac{c_j^{dir} \cdot (1-\eta_j)}{\eta_j} + \left(\sum_{i=1}^{n} z_{ij}^{ind,ac,a} + r_j^{ind,ac,a} \right) \cdot (1-\eta_j) + r_j^{a,dir} \cdot (1-\eta_j) \tag{5.56}$$

From equation 4.29,

$$\sum_{i=1}^{n} z_{ij}^{ind,ac} = \sum_{i=1}^{n} z_{ij}^{ind,ac,c} + \sum_{i=1}^{n} z_{ij}^{ind,ac,a} \tag{5.57}$$

and from equation 5.55,

$$r_j - r_j^{c,dir} = r_j^{ind,ac,c} + r_j^{ind,ac,a} + r_j^{a,dir} \tag{5.58}$$

Using equations 5.57, 5.58 and 4.25, equation 5.56 becomes

$$w_j = \frac{c_j^{ind} \cdot (1-\eta_j)}{\eta_j} + \frac{c_j^{dir} \cdot (1-\eta_j)}{\eta_j} + \left(\sum_{i=1}^{n} z_{ij}^{ind,ac} + r_j - r_j^{c,dir} \right) \cdot (1-\eta_j) \tag{5.59}$$

$$w_j = \frac{c_j \cdot (1-\eta_j)}{\eta_j} + \left(\sum_{i=1}^{n} z_{ij}^{ind,ac} + r_j - \frac{c_j^{dir} \cdot (1-\eta_j)}{\eta_j} \right) \cdot (1-\eta_j) \tag{5.60}$$

Equation 5.59 relates explicitly the emissions to their structural causes: the total emissions are due to the total cycling emissions (the first two terms) plus the emissions derived from the indirect structure and the consumption of the primary resources (from which the resources used for direct cycling are subtracted); it can be further compacted as

$$w_j = \left(c_j^{dir} + \frac{c_j^{ind}}{\eta_j} + \sum_{i=1}^{n} z_{ij}^{ind,ac} + r_j \right) \cdot (1-\eta_j) \tag{5.61}$$

[4] Here, $\mathbf{w}^{ind,c}$ is calculated using the indirect cycling throughput (calculated in equation 4.75) and then using equation 4.25 instead of using equation 4.73 so that the direct and indirect cycling emissions can be added at a later stage.

Thus, for a given level of final production, the more pre-consumer cycling, the more emissions are generated, reducing the resource efficiency of the overall system as argued in section 4.4.4 and demonstrated in section 5.4.1. So, when aiming to reduce the level of emissions without reducing final production, identifying and reducing the pre-consumer cyclic structure is a new option to consider for policymaking.

Chapter 6

Improving the resource efficiency of the economic system through structural change

6.1 Introduction

The aim of this chapter is to provide an illustrative example on how to perform a structural analysis enabling researchers to better understand the structural drivers of emission generation and resource consumption and, more importantly, to identify how to improve the resource efficiency of the economy by altering its (meta-)structures. This chapter also illustrates how to use the methods developed in chapters 3, 4 and 5 for that purpose.

The dataset used for this illustration is the same dataset presented in section 3.2.2.3 representing the Italian economy. The dataset has three sectors (agriculture, manufacturing and services) which is sufficient to illustrate the functioning of an economy but it is complex enough to mask possible systemic solutions.

The advantage of a three sectors dataset is that it enables readers to reproduce the calculations manually, which is crucial for academic understanding and cross-checking of the new body of knowledge suggested in this thesis. Additionally, in order to facilitate the reproducibility of results and the examination of the underlying mathematical formulations, the calculations and drawing of circular diagrams presented in this chapter have been programmed in Metab-X, a software specially developed during this thesis, available as open-source software (see appendix C for more information). The software is bundled with the same dataset presented in table 3.4 but can be used on any PIOT.

The first part of the structural analysis (section 6.2) uses the product-based decomposition (c.f. section 4.3) to understand the systemic relationships between the different product-based structures and the complete productive structure of the Italian economy. In particular, the contribution of each product-based structure to the total emissions, resource consumption and resource efficiency are explored. Then, the meta-structural decomposition developed in section 4.5 is used to assess the role of the cyclic structure in emission generation and resource consumption.

The second part of the analysis (section 6.3) combines the findings of the first part of the analysis with the analysis of the circular diagrams representing the meta-structures to determine which meso-intensities could be reduced to improve the macroscopic resource efficiency of the economic system or reduce the generation of selected emissions (or consumption of selected resources), i.e. it is exemplified how to improve the resource efficiency of the economic system by modifying its underlying physical structure.

Again, in this chapter, the term *disposals to nature* refers to all material flows that the economy releases back to the environment and it can be used interchangeably with the terms *waste* and *emissions* .

6.2 Understanding the physical metabolism of the economy

An implication of the product-based decomposition is that the same physical structure can have different environmental impacts (resource consumption and emission generation) depending on how the economy is driven. However, these impacts are in turn determined by the physical structure itself. In other words, the physical metabolism of the economic system is determined by both the underlying physical structure of the economic system and how the system is being driven (e.g. which final products are being produced and in which intensity). The following analysis aims to understand the physical metabolism of the Italian productive system by studying both its structure and production drivers.

6.2.1 Associating the macroscopic properties of the economic system to the product-based structures

In a productive structure whose purpose is to produce final goods, the production of each final good is the driver of the actual activity. Thus, since the product-based structures reveal the activity related to the production of each final product systemically, they constitute the analytical tool to relate the generation of emissions and requirement of resources to the production drivers — understood as the production of specific final goods.

In other words, one can assess which final goods drive the extraction of specific resources and the generation of specific emissions.

While it is possible to to calculate each of the emissions and primary resources associated to each final good independently, calculating and comparing all product-based structures constitutes an analytical framework which makes it possible to compare and analyse systematically the influence of final production in the emission generation, resource consumption and macroscopic resource efficiency of the original structure.

For each analysis that follows, a relative and absolute analysis is performed. The relative analysis reveals which final production is proportionally more intensive in generating emissions, consuming resources or has higher resource efficiency. Identifying sectors that yield emissions or require resources intensively is key from an environmental perspective, since it helps focussing policy efforts on emission intensive activities. However, these sectors are not necessarily the ones generating the most emissions or consuming the most resources since they might have a small absolute weight in the final composition of the complete structure. Thus, an absolute analysis is also required to identify the sectors generating most emissions and consuming most resources, or affecting most the macro-efficiency in absolute terms.

Comparing the relative and absolute emission structures allows for determining the product-based structures contributing the most to emission generation in relative and absolute terms. It also allows for identifying which product-based structures induce most emissions of a given type.

To start the illustration, the product-based decomposition developed in section 4.3 is applied to the Italian PIOT (table 3.4), resulting in three product-based structures: one for agricultural final goods, one for manufacturing final goods and one for services final goods (c.f. tables 4.9, 4.10 and 4.11 correspondingly) and their actual contributions (c.f. tables 4.12, 4.13 and 4.14 correspondingly). The complete structure also corresponds to the linear combination of the product-based structures (c.f. equation 4.20).

6.2.1.1 To understand the emission generation of the economic system

To compare the different types of emissions, the emissions of each product-based structure and of the complete structure are normalised by the total amount of emissions of that structure. The figures are thus output percentages and are presented as a stacked bar-plot to represent the *relative emission structure* of the product-based and complete structures in figure 6.1.

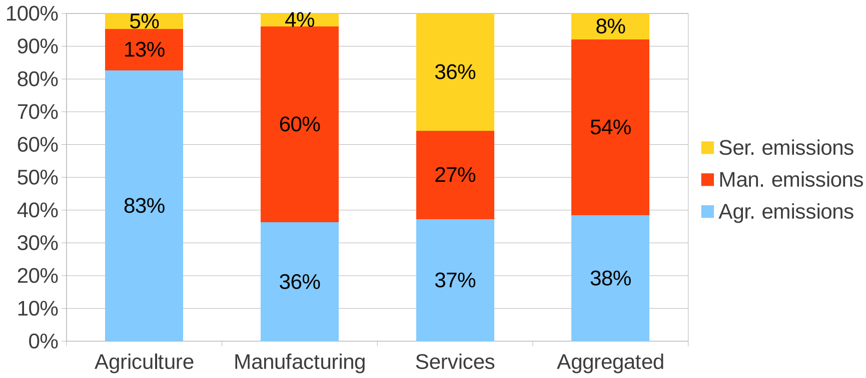

FIGURE 6.1: Relative emission structures of the product-based and aggregated structures of the Italian PIOT without final goods in million tons

It is observed that although each final product generates relatively more emissions of its sector type (e.g. the agricultural product-based structure generates mainly (83%) agricultural emissions), the emission mix differs considerably. In particular, the emissions from the agricultural and manufacturing product-based structures are dominated by the emissions generated by the sector producing the final goods, the services sector emissions being marginal in both cases. On the other hand, the services product-based structure generates emissions of all types in a significant manner (36%, 27% and 37%). In other words, it is the services sector that produces more emissions indirectly — a result matching the high degree of backward linkage found in section 3.2.4. So, the emissions generated by each product based structure reveal indirectly the backward linkage of that sector with other sectors.

Comparing the relative emission structures, the final production contributing most to agricultural emissions is the agricultural goods' production, the final production contributing most to manufacturing emissions is the manufacturing goods' production, and the final production contributing most to services emissions is the services goods' production. However, the services product-based structure generates more agricultural emissions than services emissions. These emission generation patterns arise from observing the emission structure of the product-based structures, but could never be perceived by analysing the original PIOT directly. Hence, the relevance of using the product-based structures as a comparative analytical framework.

However, although being aware of the relative contribution is key to understanding the drivers behind the total emissions, the same analysis must be performed in absolute values to understand the absolute emission structure. Below, the analysis of the emission structure in absolute terms is performed.

The *absolute emission structure* is constituted by the actual contribution of each product-based structure to each emission type (c.f. section 4.3) and of the complete structure. In figure 6.2, the *absolute emission structure* of the product-based and complete structures are presented as a stacked bar-plot.

Figure 6.2 reveals the much higher absolute weight of the manufacturing output compared to the weight of the agricultural or services sector. This explains the relative weight of emissions in the complete emission structure of figure 6.1: the relative generation of each type of emissions is close to the mix of the manufacturing sector because it is the dominant sector in absolute terms. Thus, in this case, it is concluded that manufactured goods are the main driver behind all emissions, except for the services emissions where the services sector accounts for more than half of them.

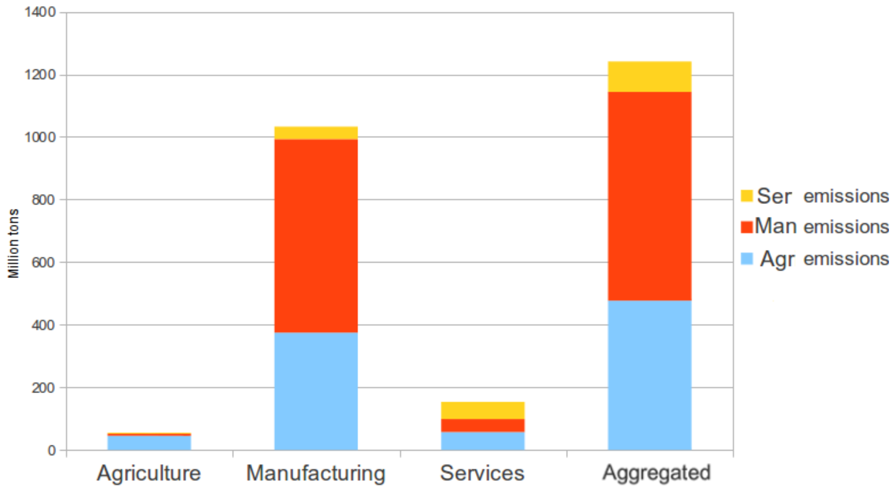

FIGURE 6.2: Absolute emissions structures of the product-based and aggregated structures of the Italian PIOT in million tons.

6.2.1.2 To understand the resource consumption of the economic system

This section's analysis is similar to the previous analysis, but focusses on the resource consumption of the economic system.

To start the relative analysis, the primary inputs of each structure are normalised by the total amount of primary inputs of the same structure and are plotted in figure 6.3 as a stacked bar plot to represent the *relative resource structure* of the product-based and complete structures; the figure values are thus input percentages.

Figure 6.3 reveals that producing agricultural final goods requires mostly (78%) agricultural primary resources, producing manufacturing final goods requires mostly (68%) agricultural primary resources but producing services final goods requires mostly manufacturing primary resources (35%) and agricultural primary resources (34%). In other words, the agricultural product-based structure is the one contributing most to the agricultural emissions in relative terms, the same applies to the manufacturing and services product-based structures. However, similarly to the analysis of the emissions, the key to understanding the relative use of primary resources by the complete structure relies on the combined study of the relative and absolute requirements of primary resources.

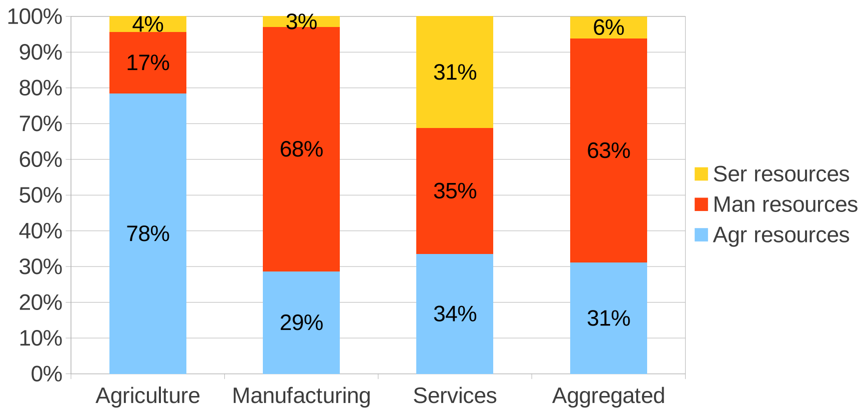

FIGURE 6.3: Relative resource structure of the product-based and aggregated structures of the Italian PIOT

The *absolute resource structure* is constituted by the absolute consumption values of each resource type for each product-based structure and of the complete structure. In figure 6.4, the *absolute resource structure* of the product-based and complete structures are presented as a stacked bar plot; the figure values are in million tons.

It is found that the main driver behind most resource requirements is the manufacturing sector and the services sector is responsible for more than half of the service resources extraction.

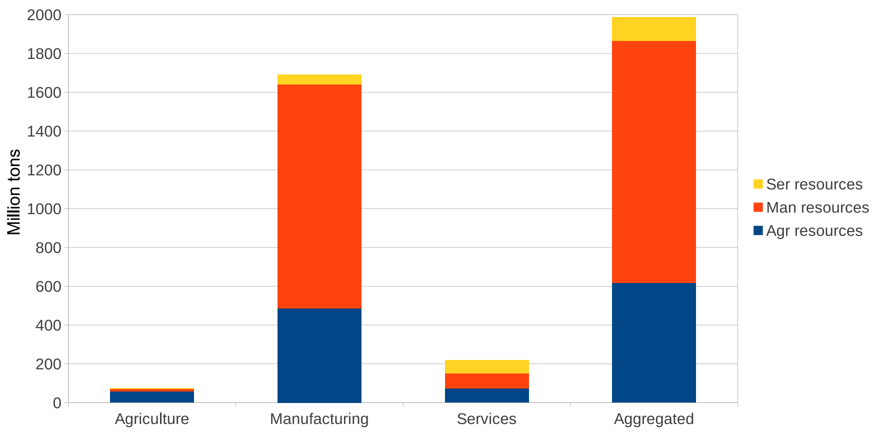

FIGURE 6.4: Absolute resource structure of the product-based and re-aggregated structures of the Italian PIOT in million tons

6.2.1.3 To understand the macroscopic resource efficiency of the economic system

The idea of this section is to assess which final good has a better systemic resource efficiency and assess the contribution of each product-based structure in the macroscopic resource efficiency of the economic system.

The resource efficiency of each product-based structure can be derived by using equation 5.1. The macro-efficiencies of the product-based and complete structures are:

$$\eta_{agr}^{macro} = 27\%$$
$$\eta_{man}^{macro} = 39\%$$
$$\eta_{ser}^{macro} = 30\%$$
$$\eta_{agg}^{macro} = 38\%$$

The macro-efficiency of the complete structure also corresponds to the weighted average of the product-based macro-efficiencies (c.f. equation 5.24).

Again, the contribution of each product-based resource efficiency on the complete, aggregated structure can only be understood by mixing the relative information with the absolute information. In this case, the main driver behind the macroscopic resource efficiency of the productive structure is the macro-efficiency of the manufacturing product-based structure due to its dominant contribution to the total material flows of the economy.

6.2.1.4 Strategy option: final demand reduction

Thanks to the analysis of the absolute and relative contribution of the product-based structures to the original structure, policies can be devised either to reduce the total level of emissions generated or resources consumed (i.e. improve the resource efficiency of the economy), or reduce the level of targeted emissions or resources.

The policies would aim to reduce the final production of selected product-based structure(s) according to the targeted macroscopic properties (e.g. macro-efficiency) or structure (e.g. required less resources of a given type or generate less emissions of a given type). For example, the product-based structure producing relatively more emissions of a given type can be targeted to reduce the total emission of this type, since lowering the activity of that product-based structure by lowering its final production would result in a reduction of the targeted emission relatively higher than by reducing other product-based structures; the same reasoning applies to resource consumption. Similarly, the activity of the product-based structure being less resource efficient can be reduced to increase the resource efficiency of the aggregated structure.

Reducing the activity of a product-based structure by reducing its final production is particularly useful when substitution options between final products are available (e.g. substitute a wooden table by an iron table). In this case, different policies could be deployed to shift the final production from a given product into another having a product-based structure producing less emissions of the targeted type or having a higher resource efficiency.

Policies focussing on reducing final production as a way to reduce systemic effects can be further refined into policies focussing into the meta-structures that reduce systemic effects without reducing final production. These might be more interesting strategy options since substitution between final goods is not always possible. In section 6.3, the meta-structures are analysed to devise such policies but before the final demand reduction options are exemplified in the following paragraphs:

As an exercise, if the emission type 1 was to be reduced, the product-based structure whose activity should be reduced by lowering its final production would be the agricultural product-based structure, since it is the one producing relatively more emissions of type 1 (83% in figure 6.1). Similarly, if the emission type 2 were to be reduced, the manufacturing product-based structure is the one to target (60%), and if emission 3 were to be reduced, the services product-based structure is the one to target (36%).

In this particular case, since most of the activity is concentrated in the manufacturing product-based structure, there is not much room to reduce emissions by reducing the agricultural or services product-based structures. However, in more disaggregated PIOTs, the activity level is more evenly distributed between different activity sectors and, thus, such analysis will provide more feasible strategy options.

As a different exercise, if the macroscopic resource efficiency of the economy was to be improved, the product-based structure(s) with better macro-efficiencies should be favoured. In this case, it is the manufacturing product-based structure which has a better macro-efficiency (39%) and, it is already the one dominating the flows of the productive system, since it is the one producing more final goods (658 million tons against 20 and 67). Thus, the macro-efficiency of the productive system is already close to the maximum it can get given the available product-based structures (38%, very close to the 39% of the manufacturing product-based structure).

6.2.1.5 Arising questions

The analysis of the macroscopic properties based on the product-based structures raises two main questions.

First, the macro-efficiencies of the product-based structures contrast with the meso-efficiencies[1], which are much higher:

$$\eta_{agr}^{meso} = 45.2\%$$
$$\eta_{man}^{meso} = 71.1\%$$
$$\eta_{ser}^{meso} = 58.9\%$$

In other words, it seems that the macro-efficiency of the whole system is lowered by its internal interactions. This is aligned with the discussion in section 4.5 and at the end of section 5.4.1, where it was pointed that the cyclic and indirect meta-structures lower the macroscopic resource efficiency. Thus, a detailed analysis of the cyclic–acyclic and direct–indirect meta-structures might provide clues on how to improve the resource efficiency of the productive system or reduce emissions of a given type. Such analyses will be performed in section 6.2.2

Second, since the economic system is rich in sectoral interactions during intermediate production[2], it is expected that a significant part of the resources initially extracted by one sector end up in a different one; in other words, the resource consumption structure of each product-based structure differs from its emission structure. So, modifying the indirect structure could constitute another option to reduce the extraction of specific resources or the generation of specific emissions, or even to improve the resource efficiency of the economic system. However, when the emission structure (calculated as the proportion of each emission type relative to the total emissions of each product-based structure, presented in figure 6.1) are compared to the resource structures (figure 6.3), it is found that the relative resource structures of the product-based and re-aggregated structures are extremely similar to their relative emission counterparts, contradicting the initial expectations. To understand this apparent contradiction, a detailed analysis of the indirect–direct structure is required.

[1]The meso-efficiencies are calculated using equation 4.54. Note there is no meso-efficiency for the aggregate structure since, by definition, meso-efficiencies relate to each sector.

[2]The proportion of intermediate flows over total flows ($\sum_{i=1}^{n}\sum_{j=1}^{n} z_{ij} / \sum_{i=1}^{n} \underline{x}_i$) in the current example is 0.42

6.2.1.6 To understand the intersectoral structure

This analysis is not directly linked to the strategy options associated to the product-based structures but can bring further insights into the intersectoral linkages of the system.

Since the circular diagrams devised in section 3.3 provide a visual representation of the intersectoral structure and its linkages with the "external structure", i.e. primary inputs and final outputs (emissions and final goods), they are used to analyse visually the intersectoral flows of the different product-based and original structures. The structures (in this case, the product-based and complete structures) should be plotted with the same options to allow for comparison.

To start with, a normalised view can be used to understand the relative contribution of each sector within each product-based structure and identify structural patterns or stylised facts. The symmetrical view is recommended since, as shown in section 3.3.3, it enables researchers to perform visually a direct forward and backward linkage analysis of the intersectoral flows. The non-normalised or merged (i.e. non-symmetrical) representations can also be used to assess the absolute weight of patterns identified in the previous analyses.

To apply this analysis to the current dataset, the symmetrical, normalised circular graphs associated to each product-based and complete structures are drawn using Metab-X and Circos[3] and put together in figure 6.5.

The first pattern identified is that all product-based structures including the actual structure have the same direct backward linkages, not only as aggregate value — which is the direct backward linkage measure of the productive system calculated in section 3.2.4.2 — but also identical in the proportion of flows composing it — the new information provided by the visual analysis. In other words, the only varying part of all structures is the inter-sectoral output structure; thus, each product-based structure can be characterised by its direct forward linkages.

This is an unexpected finding — although logical. Unexpected because one would intuitively assume that each product-based structure requires different inter-sectoral allocation of materials. However, since all product-based structures stem from the same original structure (i.e. technical coefficients and Leontief inverse matrices), the total and direct backward linkages are consequently the same between the product-based and re-aggregated structures. Thus, this finding is coherent with the model's assumption of homogeneous goods production because it implies a fixed input recipe, leaving only room for the variation of intermediate flows on the forward linkages. In other words,

[3]See appendix C for instructions on how to reproduce the diagrams.

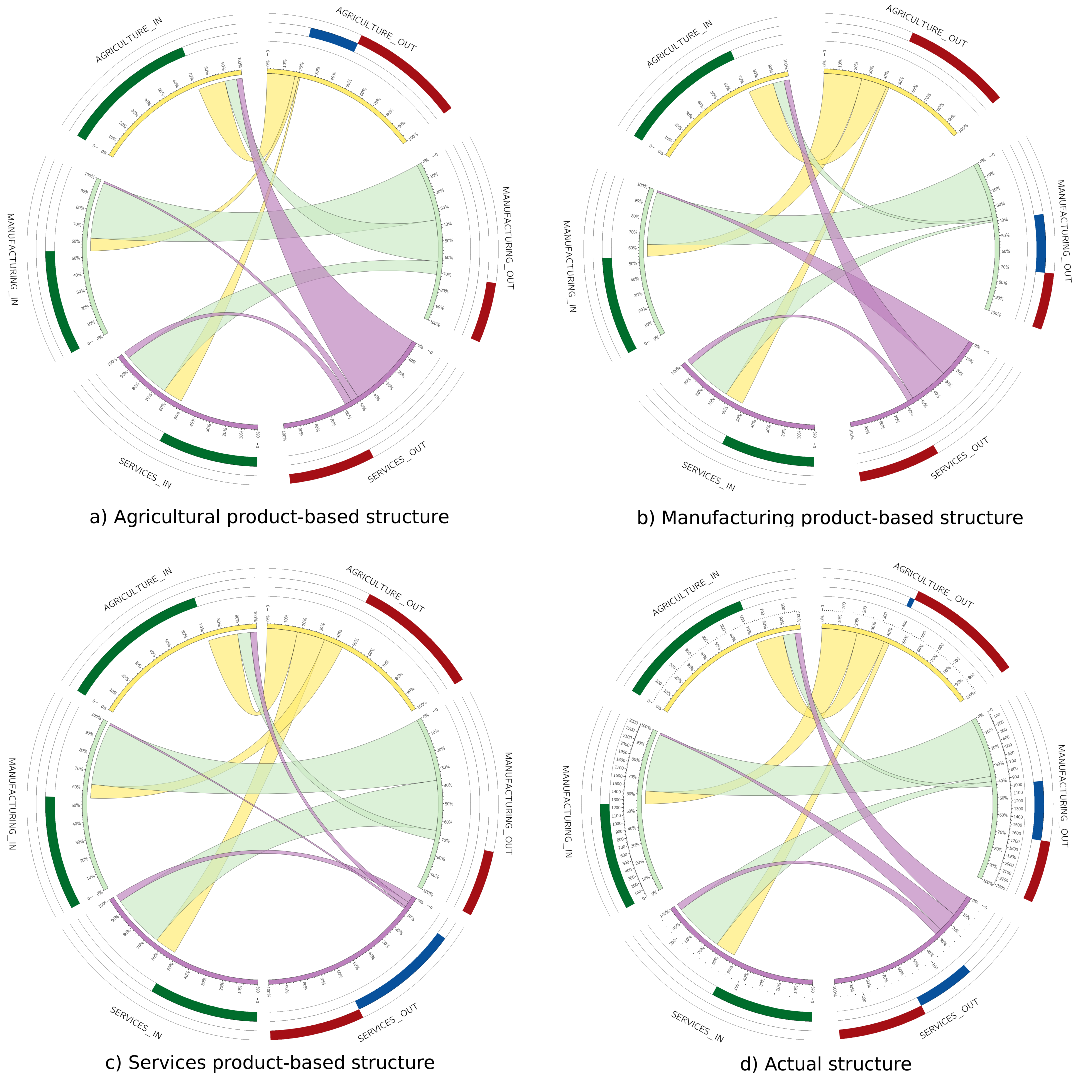

FIGURE 6.5: Circular representations of the product-based structures and re-aggregated structure of the Italian physical structure (normalised, symmetrical).

only the direct forward linkages — i.e. the intersectoral output structure — vary between product-based structures, since they represent the allocation of intermediate resources to produce a specific final good. On the other hand, the disaggregated view of the input requirements of each sector (both of intermediate and primary inputs) reveal the input "recipe" of each sector, the same across product-based structures.

Another pattern that can be observed is that the proportion of emissions generated by each sector is the same in the three product-based structures and in the re-aggregated structure: all structures generate 56% of emission 1, 29% of emission 2 and 41% of emission 3 of its total outputs. The explanation is because each sector has a fixed input "recipe" and a fixed meso-efficiency; thus, the structure of the emissions generated by the system is independent from the amount and type of goods it produces. This finding reveals a relevant structural feature: the composition of the emissions generated by a given sector are pre-determined by its input structure. So, the visual exploration of the circular diagrams helped understanding the physical structure and metabolism of the system.

But, how is it then possible that each product-based structure generates different amounts of emissions, as seen previously in the emission structure bar plot, figure 6.1? The answer can also be given visually, by plotting the same diagrams but in the non-normalised mode, see figure 6.6. This figure shows the total contribution of each sector to the final emissions, which are generated in a different proportion than the ones shown in the normalised figure. The answer can be found in the same figure: the absolute weight of each sector is different depending on the product-based structure and, thus, the proportion of emissions generated is altered when the figure is scaled to its actual values. This can be explained algebraically by the fact that the total throughput of each sector ($\underline{x}_i$) is different depending on the product-based structure. For instance, $\underline{x}_1$ is different in the agricultural, manufacturing and services product-based structures; and, more importantly, the relative importance of the three total throughputs of each product-based structure also varies, determining a different absolute composition of the total emissions. In this particular case, $\underline{x}_1 > \underline{x}_2 > \underline{x}_3$ for the agricultural product-based structure, $\underline{x}_2 > \underline{x}_1 > \underline{x}_3$ for the manufacturing product-based structure, $\underline{x}_2 > \underline{x}_3 > \underline{x}_1$ for the services product-based structure and $\underline{x}_2 > \underline{x}_1 > \underline{x}_3$ for the re-aggregated structure. To sum up, the composition of emissions is related to the structure (and to the direct backward linkage of each sector) but the amount of total emissions is also determined by the total output of the sector, which also depends on the amount of final goods produced.

6.2.2 Associating the level of emissions and resource consumption of the economic system to its meta-structures

In section 6.2.1.5, the analysis of the product-based structures raised two main questions: why is the macro-efficiency so low compared to the meso-efficiencies; and why is there so little reallocation of flows given the amount of intersectoral exchanges. In this section, a deeper structural analysis using the meta-structural components is performed to answer these questions.

In this section, the meta-structural decomposition developed in section 4.5 is applied to all product-based structures. The meta-structural decomposition of the physical structure of the economic system is then found by re-aggregating the meta-structural sub-components of the each product-based structure as explained in section 4.5.1. The meta-structural decomposition of a PIOT into the meta-structures of its product-based structures and

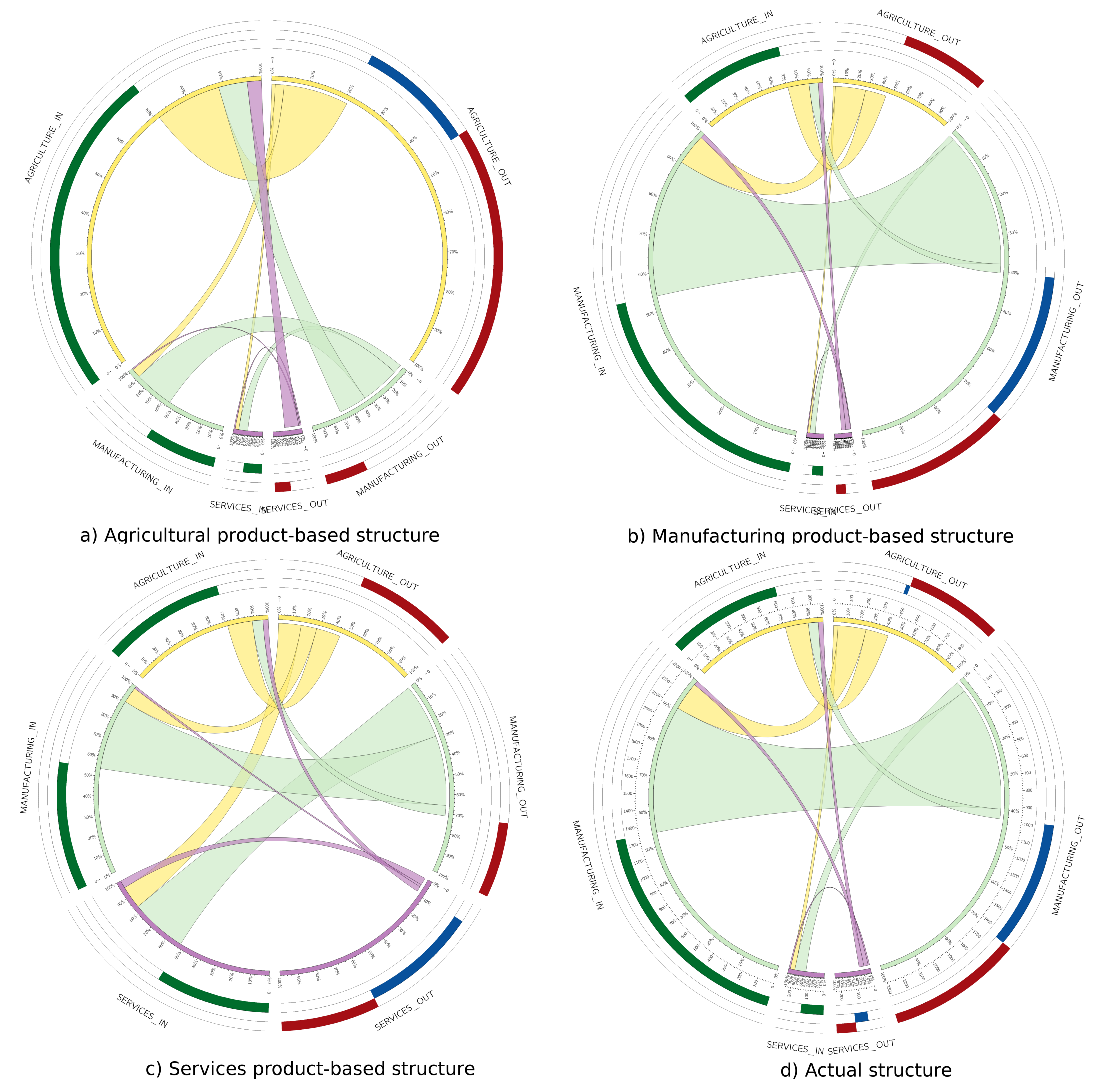

FIGURE 6.6: Circular representations of the product-based structures and re-aggregated structure of the Italian physical structure (non-normalised, symmetrical).

re-aggregation into the meta-structural components of the original structure can be performed by using the software developed during this research: Metab-X, see appendix C. The tables for each meta-structural component of each product-based structure and the re-aggregated structures can be found in appendix B.

The indicators developed in section 5.3 are calculated and presented in table 6.1. They are analysed to understand the role of each meta-structure in the physical metabolism of the economy. Recall from section 5.3 that the first indicator set reveals whether the core of the meta-structure is structurally significant. The second indicators uncovers its degree of systemic linkages. The third indicators reveals the impact of the meta-structure, i.e. how many emissions are induced by that meta-structural component. By analysing these indicators, the reallocation of resource amongst different emissions and the differences between the macroscopic and mesoscopic resource efficiencies can be understood, e.g. to identify which meta-structures cause the difference between the macro-efficiency and the meso-efficiencies.

6.2.2.1 On the cyclic structure

At the aggregate level, cycling flows take 87% (CRIx) of the intersectoral flows (more if the indirect effects of cycling ($\mathbf{Z}^{ind,c}$ and $\mathbf{Z}^{ind,ac,c}$) are also considered). In other words, the cyclic structure dominates the intersectoral structure of the economy. Additionally, the cyclic inter-sectoral flows represent also a major part (37%, CAIx) of the total flows of the economy.

About 65% (CERIx) of the emissions are due to cycling, so the cyclic structure also dominates the emissions of the system. The emissions also represent a major fraction of the total flows of the system (24%, CLIax).

This high amount of cycling justifies the low resource efficiency of the system (38%) compared to the sectoral (meso-)efficiencies (between 45% and 71%) since in this case the cycling emissions correspond to pre-consumer cycling emissions, i.e. are generated just to maintain cycling without producing final goods, consequently lowering systematically the resource efficiency of the macroscopic structure. This observation is also aligned with the structural relationships between the resource efficiency and emissions found in equations 5.46 and 5.47, which constitute the theoretical link between the macroscopic efficiency of the system and its structural components.

The Cycling Connectivity (CC) indicator is relatively low (19%), so another aspect of the cycling is that it is concentrated mostly as self-cycling. In other words, reducing the cycling throughput of a given sector will have less systemic effects than if the CC was high because it will mostly reduce its self-cycling and have little connection with the cycling throughputs of the other sectors.

Finally, to understand the cyclic structure of the economic system, the contribution of the cyclic component of each product-based structure needs to be analysed. The analysis is similar to the one performed in section 6.2.1 because the structure of the economic system is the linear combination of each product-based structure times the final goods produced by the corresponding product-based structure (c.f. equation 4.17) so are the components of the meta-structures (c.f. section 4.5.1). The intensity and the index indicators are a weighted average of the product-based structure indexes (c.f. section 5.4). In this example, the re-aggregated structure is dominated by the structure of the manufacturing sector since it produces 658 million tons over 745 in total. Thus, the CCIx from the

Structures:	Aggregated	Agriculture	Manufacturing	Services
Final outputs (million tons)				
Goods	745	20	658	67
Resource efficiencies				
Mesoscopic	-	0.45	0.71	0.59
Macroscopic	0.38	0.27	0.39	0.30
Structural indicators related to the Cyclic Structure				
Cycling (amount of cyclic flows)				
Intensity (CIy)	1.63	1.56	1.69	1.56
Rel. Index (CRIx)	0.87	0.82	0.90	0.65
Abs. Index (CAIx)	0.37	0.28	0.38	0.27
Systemic spread of the cyclic structure				
Cycling throughput	1.67	1.56	1.69	1.56
Cyclic Connectivity (CC)	0.19	0.25	0.18	0.27
Cycling Emissions (emissions due to the cyclic structure)				
Intensity (CEIy)	1.09	1.44	1.07	1.16
Rel. Index (CERIx)	0.65	0.53	0.68	0.51
Abs. Index (CEAIx)	0.24	0.26	0.24	0.20
Comprehensive Cycling (total flows due to the cyclic structure)				
Intensity (CCIy)	2.87	3.16	2.86	2.86
Index (CCIx)	0.63	0.56	0.64	0.50
Structural indicators related to the Indirect Structure				
Reallocation (amount of intersectoral indirect flows)				
Intensity (RIy)	0.24	0.33	0.18	0.84
Rel. Index (RRIx)	0.13	0.18	0.10	0.35
Abs. Index (RAIx)	0.05	0.06	0.04	0.15
Systemic spread of the indirect structure				
Reallocation Index (RIx)	0.09	0.09	0.07	0.26
Reallocation Emissions (due to the indirect structure)				
Intensity (REIy)	0.39	0.40	0.34	0.97
Rel. Index (RERIx)	0.24	0.14	0.22	0.42
Abs. Index (REAIx)	0.09	0.07	0.08	0.17
Comprehensive Reallocation (total flows due to the indirect structure)				
Intensity (CRIy)	0.73	0.81	0.58	2.20
Index (CRIx)	0.15	0.14	0.13	0.39

TABLE 6.1: Indicators related to the cyclic and indirect meta-structures for the re-aggregated and product-based structures of the Italian PIOT (table 3.4).

manufacturing sector is 64% and is lowered by getting mixed with the agricultural (56%) and services (50%) sectors to reach the aggregate amount of 63%.

Additionally, according to section 5.4.1, the theoretically maximal efficiency without pre-consumer cycling would be of 63.4% compared to the current 37.5%; in other words, there is room to improve the macro-efficiency of the system by reducing its pre-consumer cyclic structure.

6.2.2.2 On the indirect structure

According to the discussion of section 4.5.1.2, the indirect meta-structure influences both the efficiency and the resource reallocation within the system.

The indirect structure affects the macro-efficiency in two ways: through its cyclic component (the cyclic–indirect structure) and through the acyclic component (the acyclic–indirect structure). As argued previously, the former reduces the macro-efficiency since it uses primary resources to maintain cycling indirectly without producing final goods. The latter reduces the efficiency since the same flow cascades through several intermediate processes, each producing emissions and thus reducing the useful output. Both aspects are captured in equations 5.46 and 5.47, which establish a formal relationship between the macro-efficiency and the different structural components, as discussed in section 5.4.1. Both effects are captured in the indicators of the indirect structure.

Here, the indirect meta-structure of the re-aggregated structure represents 13% (RRIx) of the intersectoral flows and 5% (RAIx) of the total flows. The emissions due to the indirect structure represent 24% (RERIx) of the total emissions and 9% (REAIx) of the total flows. Thus, the indirect structure contributes to reducing the resource efficiency of the system, but not as much as the cyclic component of the structure (which induced 65% of the emissions (CERIx), as seen in the previous section).

Regarding the reallocation of flows: the most relevant indicator is the RIx which shows the percentage of flows reallocated on the final outputs (both final goods and emissions); the result is low: 9% of the intersectoral flows are re-allocated. The explanation is straight forward: only 13% (RRIx) of the intersectoral flows belong to $\mathbf{Z}^{ind}$ so only a fraction of these can be reallocated (the 9% represented by RIx).

6.3 Altering the physical structure of economies to improve its resource efficiency

6.3.1 Identifying key meta-structural components to improve the resource efficiency of the physical structure of the economic system

The previous section revealed which meta-structures dominate the physical structure of the economic system (the cyclic structure in this case). The aim of this section is to identify key meso-intensities whose reduction would improve the resource efficiency of the economy more than other meso-intensities. In this case, it is the third indicator that needs to be examined. High emissions generation reduce the resource efficiency, so a higher number indicates a reduction of the macroscopic resource efficiency induced by that meta-structure. Then, the whole structure of that meta-structure needs to be analysed separately (and taking into consideration the second indicator) to identify key meso-intensities that have a greater systemic impact.

As noted in the first part of the structural analysis, the manufacturing product-based structure dominates the physical structure of the economic system in absolute terms. However, to know whether it is the cyclic structure of the manufacturing production-based structure that dominates the cyclic structure of the re-aggregated structure, the CRIx of the re-aggregated structure must be assessed against the CRIx of the product-based structures. The value for the economic system is 87%, the value of the agricultural, manufacturing and services product-based structures are 82%, 90% and 65% respectively. Since the indexed indicators of the re-aggregated structure are a weighted average of the product-based indicators (c.f. section 5.4), it can be ascertained that it is also the cyclic component of the manufacturing product-based structure that dominates the cyclic component of the physical structure of the economic system. Thus, exploring the circular diagram of the manufacturing product-based structure with the flows disaggregated between the cyclic and acyclic components would enable identification of the key meso-intensities to improve the macro-efficiency of the economy. For completeness, the re-aggregated and all product-based structures have been plotted and put together in figure 6.7 with the cyclic component of each flow drawn in green and the acyclic in brown.

By examining figure 6.7, it is found that three meso-intensities are key due to their relevance in the cyclic structure, i.e. they constitute major intersectoral cyclic flows, in decreasing order: z_{22}, z_{12} and z_{11}. z_{22} is about 6 times bigger than z_{12} and z_{11}, which are about the same size. The first meso-intensity to target is thus z_{22}. Then, although z_{12} and z_{11} are of similar sizes, z_{12} should be targeted first since it is an inter-cycling component (z_{11} is self-cyclic) and thus the reduction of the flow will directly affect the

FIGURE 6.7: Circular diagrams of the product-based and re-aggregated structures of the Italian PIOT with disaggregated cyclic and acyclic structures (non normalised, contiguous inputs and outputs, cyclic structure in green, acyclic in brown).

cycling throughputs of the other sectors sharing the cycling flow, inducing greater systemic improvement of the efficiency of the system, compared to z_{11}.

A striking feature identified in figure 6.7 that highlights the relevance of cycling is that 80% of the flows going through the agricultural sector in the re-aggregated structure belong to the cyclic structure and, thus, do not produce anything[4] [5]. Similarly, the cycling flows through manufacturing almost reach 58% of the total sectoral flows, and the cycling flows through the services sector are about 48%. In other words, the agricultural sector

[4]This measure can be read from the middle segment, which aggregates the total amount of cyclic an acyclic flows, revealing the proportion of these meta-structures over the total sectoral output.

[5]This measure is different from the indicators developed in section 5.3 and presented in table 6.1 because the indicators represent the weight of certain meta-structures over the overall structure, while the measure presented in this paragraph corresponds to the weight of the meta-structure at sectoral level.

plays the role of a "maintenance sector", i.e. a sector that does not produce many final products itself but plays a major role in the systemic functioning of the economy.

6.3.2 Identifying key meso-intensities to mitigate targeted emissions or resources systemically

Instead of targeting an improvement in the macroscopic efficiency of the economy, it might be preferred to mitigate specific types of emissions or reduce the extraction of specific types of resources, which in turn also improve the efficiency of the economy since final production is maintained. However, the indicators used in section 6.2.2 represent aggregated values and, thus, do not provide good guidance on which structures are generating specific emissions (or requiring specific resources). In this case, a more disaggregated analysis is required.

The circular diagrams can be used for that purpose. Both the intersectoral flows — i.e. the intermediate production and consumption — and the "extra-sectoral flows — i.e. final goods, emissions and resources — can be coloured according to the meta-structure they belong to. Thus, the visual exploration of such types of colour-coded circular diagrams would indicate which meta-structure is influencing most the targeted emissions (or resources). Then, the meso-intensities related to these flows can be identified.

The analysis used to reduce targeted resource consumption can also be used to reduce the emissions generated by the same sector if there is little re-allocation of resources. This is because the resources extracted are consumed and transformed by the same sector, generating emissions in the same sector, before passing the intermediate production to the connected sectors. In case there is a notable reallocation of flows, the indirect structure can be explored to identify other meso-intensities that affect the generation of emissions systematically.

A trivial manner to reduce the primary resource requirements of a sector (e.g. sector 1) is to improve its resource efficiency vis-à-vis the extraction of the resource itself, i.e. the meso-intensity of the corresponding primary resource, e.g. r_1. However, the following analysis will focus on improvements that can be achieved systemically by modifying the physical structure of the economic system. E.g., if the inter-sectoral exchanges can be analysed in a disaggregated manner, it is also possible to reduce the resource requirements of a sector by improving the efficiency of down-stream processes (i.e. of other inter-sectoral exchanges associated to the sector itself) or systemically (i.e. of other sectors).

As an exercise, the different structural decompositions are analysed to reduce systemically the demand for resource r_1. First, the product-based contributing the most to r_1 extraction is to be identified. Analysing the actual contribution of each product-based structure in the complete structure (c.f. figure 6.4), it is ascertained that the manufacturing product-based structure contributes the most to r_1 extraction (485.4 million tons extracted by the manufacturing product-based structure against 58.59 and 74 extracted by the agricultural and services product-based structures). Thus, the systemic linkages of the manufacturing are explored first since it is the structure which dominates r_1 extraction.

Since the previous indicator analysis revealed that the cyclic meta-structure dominates the inter-sectoral flows, the circular diagram representing the cyclic-acyclic meta-structure of the manufacturing product-based structure is analysed (c.f. figure 6.7). Two potential down-stream processes, i.e. meso-intensities, affecting the extraction of agricultural resources are identified: z_{12} and z_{11}. z_{11} is a self-cycling flow within the agricultural sector, so lowering its intensity reduces the cycling throughput of the agricultural sector, reducing notably the resources it requires to maintain its activity because it reduces the resource requirements but at the same time it reduces the cycling throughput, reducing even more the activity level of the sector. z_{12} is an inter-cycling and acyclic type of flow whose meso-intensity actually belongs to the manufacturing sector. In other words, it is the manufacturing sector that needs to improve its meso-intensity vis-à-vis the agricultural sector. Because z_{12} belongs to both the inter-cyclic and acyclic components, it has a deeper effect than z_{11}: improving z_{12} directly reduces the cycling throughput of the agricultural and manufacturing sectors by the same amount and thus, reducing r_1 and r_2 requirements. Additionally, improving the acyclic component implies that the agricultural sector needs to produce less intermediate goods which are embedded in the manufacturing final goods, further reducing r_1.

As a different exercise, the emissions from the agricultural sector w_1 are now to be reduced systemically. Analysing the contribution of each product-based structure in the total emission structure (c.f. figure 6.2), it is ascertained that the manufacturing product-based structure contributes the most to w_1 emissions (374.66 million tons emitted by the manufacturing product-based structure against 45.23 and 57.12 emitted by the agricultural and services product-based structures). The reallocation index (RIx) is low for the complete structure (9%) and even lower for the manufacturing product-based structure (7%). So, most probably, the same meso-intensities as in the case of r_1 can be targeted because, in the case of little reallocation, the resources extracted by a given sector are mostly consumed within the same sector. Exploring figure 6.7 indicates that the same meso-intensities should be targeted. Improving z_{11} would reduce the cycling throughput of the agricultural sector and thus the associated resource requirements and corresponding emissions. Also, improving z_{12} reduces the amount of products that the agricultural sector needs to produce for the manufacturing sector and its cycling throughput, reducing the activity of the sector and thus its emissions w_1.

6.3.3 Strategy option: inducing change in selected intersectoral linkages to systemically improve the resource efficiency of the system

Here, the strategy options made possible by this new analysis are to target specific meso-intensities (i.e. intersectoral linkages) in order to induce the desired systemic effects. Reducing a meso-intensity means to reduce the requirements of a sector vis-à-vis the intermediate production from another sector or primary resources. In other words, it means to improve the sector productive efficiency vis-à-vis the identified intersectoral flow.

Identifying the key meso-intensities inducing greater systemic effects is crucial for environmental and industrial policies aiming to reduce the environmental impact of the economic system. The meso-intensities represent a specific technological aspects of each sector: e.g. z_{21} represents the material flow required by sector 2 from sector 1, which is associated to determined technological process, different from z_{11} or z_{31}. Therefore, identifying the key meso-intensities enables policy makers to select and study specific technological aspects of sectors to devise industrial or environmental policies to mitigate the (systemic) environmental impact of the economic system. Thus, this method links the macroscopic physical structure of the economic system (represented by the IO framework) with the potential technological change that would reduce the environmental impact of the economic system systemically (but that needs to be devised in a subsequent detailed technological study).

This second part of the structural analysis has shown how to target meso-intensities in order to improve the resource efficiency of the system. In this case, the cyclic meta-structure of the manufacturing product-based structure dominates the complete structure, especially the level of total emissions, and thus, the efficiency of the system. By analysing its disaggregated cyclic structure, it has been determined that lowering the meso-intensities z_{22}, z_{12} and z_{11} would induce a significant systemic increase of the resource efficiency of the system. These are the meso-intensities to be targeted by policy makers and the focus should be on the resource efficiency of the sector vis-à-vis the intermediate resources provided (e.g. targeting z_{12} would mean improve the manufacturing sector efficiency vis-à-vis agricultural goods).

It has also been shown how to target meso-structures to reduce selected emissions. In this case, the focus of the analysis has been to assess the systemic linkages related to the selected emissions (or resources) rather than to the whole system. In this case, it has been determined that lowering the meso-intensities z_{12} and z_{11} would induce a significant reduction of emission w_1 and also of resource consumption r_1.

Chapter 7

New insights for material flow management

7.1 Introduction

In the introductory section (chapter 1), it was stated that the aim of this thesis was to identify how to improve the resource efficiency of the economy by altering its physical structure, i.e. to identify how can production and consumption activities be decoupled from the environmental impact they currently induce. However, in order to achieve this aim, several intermediate milestones needed to be achieved. First, there was a need to make clear how to analyse and characterise the physical structure of the economic system (c.f. section 1.4, further developed in sections 2.3 and 2.4), and, second, it was also required to characterise explicitly the full cyclic structure of the economic system (c.f. section 1.4, further developed in sections 2.5 and 2.6).

Therefore, the first methodological chapter (3) aimed to understand how to characterise and analyse the physical structure of the economic system using the input-output framework. Previous literature was not conclusive (and even misleading) about which input-output methods or models could be applied to Physical Input-Output Tables (PIOTs) (c.f. section 2.4.2.1) so, in chapter 3, it is demonstrated which are the two only methods that can be applied to PIOTs to gather correct results (sections 3.2.1.3 and 3.2.2). It also also demonstrated that only one of these methods is valid to analyse the physical structure of the economy and this method constitutes a new IO model making it possible to trace by-products as final products (section 3.2.4). Both methods are generalised to analyse PIOTs with several simultaneous disposals to nature (section 3.2.5). Additionally, in section 3.3, a visual representation of PIOTs is developed enabling researchers to perform disaggregated structural analyses and identify structural patterns. All these developments contribute to understand how to analyse the physical structure of the economic system using the input-output framework.

Then, in chapter 4, it is aimed to identify the full cyclic structure of the economic system. In section 4.2, building on a previous method to identify the intersectoral cycling, a new method is suggested which removes previous computational restrictions and quantifies the exact amount of cycling (the previous method overestimated the intersectoral cyclic structure and underestimated the acyclic intersectoral structure). In section 4.4, the resources and emissions associated to the intersectoral cyclic structure are calculated and it is demonstrated that two types of cycling exist (pre-consumer and post-consumer cycling), each affecting differently the resource efficiency of the economy. Finally, in section 4.5, a structural decomposition is suggested to identify the full cyclic structure. However, it is found that the previous understanding on how to extract the cyclic structure was misleading since the acyclic remainder of the intersectoral structure does not fully belong to the acyclic structure, but partly to the cyclic. Therefore, two intertwined sub-structures exists: the cyclic-acyclic and the direct-indirect; this constitutes the main theoretical advancement provided by this thesis. A method to identify the cyclic-acyclic and direct-indirect components of a PIOT is developed in section 4.5.2. So, the developments provided in this chapter help researcher to better understand how the physical structure of the economy works and to quantify the full cyclic structure and other sub-structural components.

The underlying aim underpinning the identification of the cyclic structure was to quantify the environmental impact associated to the cyclic structure using the primary resources and emissions associated to the cyclic structure as proxies. In chapter 5, a set of indicators characterising the weight of the cyclic and indirect sub-structures on the overall structure were developed (section 5.3). These will help researchers understand how each sub-structure affects the overall performance of the economy. Then, is section 5.4, the different sub-structures are mathematically related to the emission generation and resource efficiency of the economy, enabling researchers to understand which structures are to be minimised or maximised to reduce the environmental impacts of the economy. So, the developments in this chapter provide the analytical tools to identify which sub-structural components are to be altered in order to minimise emissions and improve the resource efficiency of the economy.

Finally, in chapter 6, it is illustrated how to apply the IO methods reviewed and developed in chapter 3, the structural decompositions developed in chapter 4, and the indicators and relationships established in chapter 5 to identify how to improve the resource efficiency of the economy systemically. The illustrative analysis is performed on a three sector PIOT representing the Italian economy.

The implications of the findings of each chapter are discussed in the following sections. The findings of chapter 4 are discussed within section 7.2. However, since these are intimately linked to the developments of chapter 5, the new relationships established between the sub-structural components and the macroscopic behaviour of the system are discussed in section 7.2.1.1 and the set of indicators developed are discussed in section 7.2.1.2. The new understanding concerning how to use IO methods/models with PIOTs developed in chapter 3 are discussed in section 7.3 and the circular diagrams developed also within that chapter are discussed in section 7.4. Finally, some suggestions to expand the analytical framework are discussed in section 7.5.

7.2 Towards understanding the systemic effects of cycling and other structural components

Current literature suggests that cycling improves the environmental performance of the economic system since it reduces resource consumption and emission generation to produce a given amount of final products (c.f. section 2.5.1, WRAP (2010)). This idea underpins current environmental and industrial policies aiming to transition towards a more environmentally friendly economy by creating a circular, closed loop arrangement of its material flows. E.g. Japan's Sound Circular Economy (Ministry of the Environment, 2003, 2008), the EU 3R economy (IEEP et al., 2010) and Scotland's Zero Waste Plan (Scottish Government, 2010) all share the idea to develop a strong waste management system strongly based on recycling. However, current methods only provide a partial characterisation of the cyclic structure of the economic system (c.f. section 2.6). In fact, only two methods are currently available for that purpose: the Finn Cycling Index provides an aggregate measure representing all cyclic flows within the system (Finn, 1976), and an algorithm developed by Ulanowicz (1983), which identifies the cyclic paths between the system components (but not the emissions and resources associated to them). These have been broadly used until nowadays, both to characterise the level of cycling within ecosystems (Ma and Kazanci, 2014) and industrial systems (Bailey et al., 2008).

In chapter 4, a new method is developed to identify the full cyclic structure of the productive system, i.e. representing the cyclic interactions between the different economic sectors and the resources and emissions associated to these cyclic interactions (c.f. section 4.5.2). Additionally, in chapter 5 this method is used to establish the relationship between the different structural components of the economy (e.g. the cyclic structure) and the system properties (e.g. the resource efficiency), and to develop an indicator set to capture the impact of the relevant structures on the system behaviour. The underlying idea of the illustrative example provided in chapter 6 is to show how to analyse the physical structure of an economy so as to find possible strategies to improve its resource efficiency (i.e. mitigate its environmental impacts) by altering its structure.

However, more importantly, before developing the method to identify the cyclic structure, it was found that the physical structure of the economic system is composed of two overlapping sub-structures: the *cyclic–acyclic* and the *direct–indirect* meta-structures[1] (c.f. section 4.5.1), each impacting differently the properties of the overall system. This can be considered the main contribution of this work because it challenges the fundamental current understanding of how the structure of dissipative systems work.

Additionally, different types of cycling were formally characterised: *pre-consumer cycling*, *post-consumer cycling* and *trans-cycling*, each inducing different systemic effects. The idea of *pre-consumer cycling* and *post-consumer cycling* had been previously suggested in the literature (Bailey et al., 2004b) but their corresponding structures had not been identified explicitly nor formalised mathematically. The review of previous work did not reveal any explicit definition of trans-cycling, so it is the first time this type of cycling is formally defined (although some previous studies quantified cycling of systems involving different types of materials such as in Bailey et al. (2004b)).

Below, each of these advancements is summarised and discussed in the context of the current literature, presenting its implications and limitations.

7.2.1 Advancements in the understanding of the cyclic structure and its systemic impacts

7.2.1.1 Theoretical

Structural decomposition between cyclic-acyclic and direct-indirect sub-structures

The initial aim of the research was to identify the full cyclic structure the economic system; however, prior to developing such method, it needed to be understood what are the structural components within dissipative systems containing cycling. By exploring how the different structural components were linked, a new set of structural relationships were developed: section 4.5.1 argues that the underlying structure of the economic system can either be divided between a direct and indirect sub-structures or between an acyclic and cyclic sub-structures. More interestingly, these two set of structures are intertwined, i.e. each structure happens in both of the other types of structures. Therefore, the structural decomposition need to find first these overlapped structural components before being able to re-aggregate them into the two sets of sub-structures. In particular, the

[1]The concept of meta-structure refers to the structure of the structure, e.g. the cyclic structure within the overall physical structure.

first structural components to be found are the cyclic-direct, cyclic-indirect, acyclic-direct and acyclic-indirect before they can be re-aggregated either as the cyclic-acyclic or direct-indirect structure.

In this sense, equations 4.27 to 4.30 constitute the main theoretical advancement of the thesis since they imply a new understanding of how the structure of the economic system[2] works.

Previous research on structural properties of dissipative systems spans over several fields: ecological studies focussed on quantifying the amount of systemic cycling and trying to characterise its systemic properties, structural economist tried to identify important system flows (i.e. coefficients) and industrial ecologist either tried to identify the structure of specific material flows through substance flow analysis, studied recycling with simple indicators or tried to port ecological methods to study industrial systems (see section 2.6).

The methods were heterogeneous but the main issue is that there was no common understanding about the underlying sub-structural components of the structure. The main view is that the structure can be divided between cyclic and acyclic flows in a straight forward manner. This was mathematically formalised by Ulanowicz (1983) when devising a method to identify the intersectoral cyclic structure of a system (see equation 2.41, page 81). It means that, amongst all intersectoral flows ($\mathbf{Z}$) a cyclic structure exists ($\mathbf{Z}^c$) and the remainder corresponds to acyclic flows ($\mathbf{Z}^a$). However, while the remainder ($\mathbf{Z}^a$) represent *de facto* acyclic flows, part of these actually belong to the cyclic structure in the sense that they are required for the cyclic structure to be maintained. Therefore, the intersectoral flows cannot be allocated in a straight forward manner between the cyclic and acyclic structures. In fact, the remainder ($\mathbf{Z}^a$) represents indirect flows which have to be allocated between the cyclic and acyclic structures; thus, equation 2.41 has been rewritten as equation 4.27, which constitutes the starting point of the new structural decomposition suggested in this research. The literature examining the cyclic structure of dissipative systems did not comment on the direct or indirect components of the cyclic structure (Finn, 1976; Patten, 1985; Fath and Halnes, 2007; Bailey et al., 2008; Graedel et al., 2011; UNEP, 2013b).

Previous work in structural economics talk about the indirect structure but it refers to the acyclic structure only; thus, in fact, it had identified what this research calls the acyclic–indirect structure. Simpson and Tsukui (1965) discovered that the production structure represented as IOTs could be organised in block triangular matrices, revealing a specific hierarchy and dependence between sectors. This structural feature was later referred as the *degree of fabrication* (Nakamura and Kondo, 2009), since this arrangement captures the transformation of goods from a raw state into more sophisticated products (e.g.

[2] And of dissipative systems in general, such as trophic food webs.

from copper ore to copper cathode to electronic component to electronic final product). However, this representation is not necessarily accurate since the method to obtain the block triangular matrices consists of discarding the smaller coefficients of the technical coefficients matrix and, thus, it is also discarding potential cyclic interactions. So, the block triangularisation of the technical coefficients matrix masks the cyclic structure and, thus, the obtained structure does not correspond to the acyclic–indirect structure, since it entails parts of the cyclic structure. In this sense, the decomposition suggested in this work constitutes a new understanding of how the structure of the economic system works.

Relationships between the structural components and the system properties and systemic environmental impact Previous work had the common understanding that recycling improves the environmental performance of the economic system because it lowers the primary resources required and emissions generated to produce the same amount of products (i.e. it improves the system resource efficiency, see section 2.6.1). And this understanding has been backed by empirical studies, usually based on Life Cycle Analysis (WRAP, 2010; UNEP, 2013b). The issue is that the empirical analyses did not provide information on the structure of cycling and, thus, were unable to establish a direct explicit relationship between the cyclic component and the environmental impact of the economic system. Additionally, such studies mainly focussed on assessing post-consumer cycling, i.e. on (re)cycling happening after consumption. Therefore, this research has focussed instead on studying the structural properties of pre-consumer cycling.

In this research, it is the first time that a direct explicit relationship between the (pre-consumer) cyclic component and the environmental impact of the economic system is established. Thanks to the new understanding on the sub-structural elements, its mathematical formulation and the new method to calculate each of them (discussed in the next section), it was possible to calculate the impact that the cyclic structure had on the resources required and emissions generated by the system (and therefore to its resource efficiency), i.e. a direct relationship between the structure and its environmental impact has been established. In particular, in section 5.4, an explicit relationship is made between the overall resource efficiency of the economic system and the different subcomponents of the structure (e.g. the intersectoral cyclic component) and structural properties (e.g. the sectoral resource efficiencies). Also, an explicit relationship is made between the emissions generated by the economy and the different subcomponents of the structure and structural properties. Previous studies on systemic cycling used indirect measures such as path length and the Finn Cycling Index to try to relate the cyclic structure to its environmental impact (Bailey et al., 2004b). However, these are not accurate because they do not measure directly the emissions due to the cyclic structure and it is assumed that higher levels of cycling induce higher levels of emissions, but this is not necessarily true; it all depends on the different sub-structures and sectoral resource efficiencies.

The implications of these relationships are relevant for structural analysis since they enable researchers to quantify directly the systemic effects of cycling in absolute terms. In other words, the desirable structural changes can be inferred at theoretical level by studying these relationships. This contrasts with previous works which needed to make comparative studies to assess what was the best cyclic structure (Bailey et al., 2004b, 2008).

7.2.1.2 Methodological

Identification of the full cyclic structure of the productive system The original aim of the thesis was to identify how to improve the resource efficiency of the economy by altering its structure. The development of the theoretical understanding and methods to identify the full cyclic structure of the economic system has been central to that aim because the resource efficiency of the economic system is determined by its underlying cyclic structure. In particular, the theoretical understanding underlying the cyclic-acyclic and direct-indirect decomposition has been developed in section 4.5.1 and the method to identify the these sub-structures within a PIOT has beed developed in section 4.5.2.

Previously, only two methods were available to quantify the cyclic structure: either providing a partial characterisation of the cyclic structure, i.e. only of the intersectoral cyclic flows (Ulanowicz, 1983), or providing an aggregate indicator of the total amount of cycling (Finn, 1976). The former was found to overestimate the total level of cycling (c.f. section 4.2.2) and the latter was found to represent a special structural case and could not be applied to relate the cyclic structure to the algebraic properties of a system generating several final outputs simultaneously (c.f. section 4.2.3). Thus, the only possibility to identify the cyclic structure without overestimating it was to build on the algorithm originally developed by Ulanowicz (1983) to identify the intersectoral cycles accurately and then characterise the rest of the cyclic structure according to the new understanding developed on the functioning of the physical structure of the economy, i.e. that the structure can be decomposed between either a cyclic-acyclic or direct-indirect sub-structures, which overlap (see the full explanation in section 4.5 and the final discussion in section 7.2.1.1).

In particular, the following advancements were made in this research to develop the method to identify the complete cyclic structure of the economic system:

- The removal of a computational restriction of the algorithm originally developed by Ulanowicz (1983) to identify the intersectoral cyclic structure (see section 4.2.1).

- The finding that a previous structural decomposition of a system producing several final goods is required to avoid overestimating the amount of cycling (c.f. section 4.2.2). The structural decomposition is called *product-based decomposition*, since it identifies the physical structure associated to the production of a given final product. The methodology applying this decomposition to Physical Input-Output Tables is developed in section 4.3.
- The analytical determination of the resources and emissions associated to systemic cycling (see section 4.4).
- The definition of a new set of equations (4.27 to 4.30) reflecting the new understanding of the functioning of the physical structure of the economic system.

These advancements were used to develop a method to identify the cyclic-acyclic and direct-indirect sub-structures in section 4.5.2. The full decomposition has been programmed in python and released as a general public license software called Metab-X (c.f. appendix C). The resulting cyclic structure (and other structural components such as the acyclic, direct and indirect structures) constitute a novel characterisation of the cyclic structure of dissipative systems such as the economic system.

Since this method enables to explicitly identify the cyclic structure (and other sub-structural components) and to relate the structure to the environmental impacts of the economic system, it constitutes a key development to devise a transition towards a more materially sustainable economy. In particular, it helps identifying the flows that have a greater contribution to the cyclic structure and, therefore, it can help researchers and policy makers identifying and deciding which associated processes or technologies should be modified to reduce the systemic primary resource requirements and/or emissions. In other words, the methodology developed might represent the stepping stone to guide a structural change towards a more resource efficient economic system.

Indicator set quantifying the weight and the environmental impact of the cyclic and indirect structures In section 5.3, two sets of indicators were developed to characterise the systemic effects of the cyclic and indirect structures because these two sub-structures induce the "indirect" effects within the system. The two indicator sets share the same principles and contain measures quantifying the weight of the sub-structure under analysis (intersectoral flows, emissions and total flows). Each indicator is presented in its intensity and indexed forms (indexed to the same sub-structure and total flows).

First, the indicators quantifying intersectoral and total weight of the indirect and cyclic structures developed in section 5.3.2 and 5.3.3 correspondingly enable researches to have an idea of the weight of the sub-structures compared to the actual structure. Previously, only the (Finn) Cycling Index (Finn, 1976) provided an estimate of the intersectoral weight of the cyclic structure, although it was based on a different understanding of functioning of the the sub-structures and it has several limitations (see section 4.2.3). Here, the equivalent would be the Cycling Absolute Index (page 191) since it provides the ratio between the intersectoral flows associated to the cyclic structure (not necessarily cycles) and the intersectoral flows associated to the acyclic structure. However, the indicators measuring total weight of the cyclic (and indirect) sub-structures are also important since the resources and emissions related to the cyclic (and indirect) sub-structures might outweigh the ones associated to the acyclic (and direct) sub-structures.

Second, the environmental impact of the cyclic (and indirect) sub-structures can be directly measured using the emissions associated to these sub-structures, since the emissions can be used as a proxy for the environmental degradation induced by economies. This is captured by the indicators quantifying the emission associated to the cyclic and indirect sub-structures. This is the first time that an indicator directly relating the cyclic (and indirect) sub-structure to environmental degradation is devised, since previous indicators used indirect measures (such as the Finn Cycling Index) aiming to capture the amount of systemic cycling but could not provide a measure of the emissions or environmental impact associated to it and its environmental impact could only be inferred through proxy indicators which are not directly linked to the amount of emissions (Bailey et al., 2004b, 2008).

7.2.1.3 Conceptual

On pre-consumer and post-consumer cycling The theoretical and methodological advancements developed in this research constitute a formalisation of the underlying structure of the economic system and its systemic impacts, providing the theoretical support to determine the systemic impacts of different types of cycling, e.g. pre-consumer and post-consumer cycling (see section 4.4).

The different systemic effects of cycling can be intuitively explained as follows: cycling is, in principle, a more resource efficient way to produce goods than an acyclic structure since part of the discarded goods are re-used to produce a new good, saving some raw materials and increasing the resource efficiency of the system. However, this only applies when the good used to calculate the resource efficiency of the system is involved in the cyclic structure. In fact, cycling can have the opposed effect if it does not involve the goods used to calculate the resource efficiency of the system because 1) there are no resource savings vis-a-vis the good used to calculate the resource efficiency and 2) cycling requires some material flows to “feed” or “maintain” the level of cycling, reducing the resource efficiency of the system. This implies that two different types of cycling exist within the economic system:

- *post-consumer cycling*, which is constituted by cycles entailing the goods used by the final demand sectors (i.e. the household, government and gross capital formation sectors), where the "reference" material flow are the final goods. In this case, since cycling involves the "reference" material flow (goods for final consumption), it increases the resource efficiency of the overall system.
- *pre-consumer cycling*, which is constituted by cycles *not* entailing the goods used by the final demand sector, i.e. cycles occurring within the productive system, before final goods are produced[3]. In this case, since cycling does not involve the "reference" material flow (final goods), it decreases the resource efficiency of the overall system because it requires extra resources to maintain the level of cycling, and these extra resources are not embedded in final production.

Typically, the term recycling has been used to describe pre-consumer and post-consumer cycling indistinctly when analysing the material flow structure of the economic system, e.g. through substance flow analysis (Graedel et al., 2002; Daigo et al., 2010), by analysing the recycling rates of metals (Graedel et al., 2011; UNEP, 2011b) or by defining recycling in technical regulation (European Parliament, 2008). This might be due to the fact that the systemic impacts are usually calculated through Life Cycle Analysis, but LCA tends to take a product-centric approach, examining End-of-Life recycling rather than pre-consumer re-cycling (UNEP, 2013b). However, Bailey et al. (2004b), who examined the systemic properties of cycling, had argued that production and consumption cycling would have the systemic impact found in sections 4.4.3 and 4.4.4; however, his argumentation was based on the general understanding of cycling. Instead, sections 4.4.3 and 4.4.4 demonstrate mathematically why pre-consumer cycling lowers the resource efficiency of the economic system compared to more efficient acyclic flows.

Then, the issue is that the fact that pre-consumer and post-consumer cycling have different systemic effects might lead to inaccurate or self-defeating policies. For example, encouraging recycling altogether in order to improve the resource efficiency of the economic system might lead to increased pre-consumer cycling, reducing the resource efficiency of the economic system compared to the case where acyclic resource efficiency were improved. That is why Bailey et al. (2004b) suggested to use different metrics associated to production and consumption cycling. However, the issue goes beyond, in the sense that it is the very definition of recycling that should accommodate the different systemic impacts of different types of recycling. Therefore, it is suggested that recycling is redefined

[3]Some cycles occurring "after" consumption might not involve final goods: e.g. cyclic flows between waste management sectors. These are also considered pre-consumer cycling because they reduce the resource efficiency of the system even if happening after the final consumption sector.

to integrate the concepts of pre-consumer and post-consumer cycling. If this was the case, the 3R strategy (reduce, reuse and recycle) on waste management should be modified by strongly incorporating the idea that recycling should only be systematically encouraged in the case of post-consumer recycling. Only then, different types of policies could be explicitly developed to deal with the different systemic effects of pre-consumer and post-consumer cycling and to reduce pre-consumer cycling in favour of more resource efficient linear processes.

In particular, current policies aiming to implement a circular, closed loop economy based on the 3R concept (Ministry of the Environment, 2003, 2008; IEEP et al., 2010; Scottish Government, 2010) should be amended correspondingly . The formalisation on the different systemic effects of *pre-consumer* and *post-consumer* cycling affect the ideal cyclic structure of a circular, closed loop economy. The aim of a circular, closed loop economy is to lower its environmental impact by mitigating resource consumption and emission generation by improving its macroscopic resource efficiency. Thus, a circular economy should minimise its level of pre-consumer cycling while increasing its level of post-consumer cycling. This might go against the intuition that all cycling is beneficial all thus all types of cycling should be maximised, but both the discussion of the systemic effects of pre-consumer and post-consumer cycling (c.f. section 4.4.4) and the analytical derivation of the relationship between pre-consumer cycling and the macroscopic resource efficiency of the productive system (c.f. section 5.4) support this idea.

Also, it has been found in section 4.5.1 that pre-consumer cycling has different systemic impacts because it has a different function for the system. The cyclic structure represents the cyclic exchange of material flows required for productive purposes even if the materials involved are not embedded in final products. For example, the forestry sector might provide wood to the manufacturing sector, which returns part of the wood as wooden tools to the forestry sector; the rest of wooden tools and wood are sold to the household sector (c.f. figure 4.8-a). The cyclic exchange of wood is not embedded in the final products but it is exclusively used to maintain the level of production: part of the wood that is sold to the manufacturing sector is used to produce wooden tools that are sold back to the forestry sector that uses them to produce more wood. Without this cyclic exchange, the forestry sector could not keep producing. Thus, this cyclic exchange is required to maintain the level of activity of the system, i.e. the cyclic structure corresponds to the *maintenance structure*.

The idea that the cyclic structure constitutes the *maintenance structure* of the economic system is backed by the systemic properties of cycling discussed in section 4.4.3. Cycling maximises the resource efficiency of the whole system vis-à-vis the cycles themselves. At pre-consumer level, cyclic flows are not embedded in final production, so they are not productive flows; they can only help maintain the level of activity (production) of the system. So, at pre-consumer level, it is the acyclic flows that constitute the productive flows, since they represent the primary resources that are transformed and embedded (directly or indirectly) into final goods. At post-consumer level, cyclic flows can still be considered maintenance flows since they help maintaining the level of activity of the whole system at the lowest resource costs (i.e. they induce higher resource efficiency). However, at post-consumer level, the term productive flows does not apply any more since post-consumer acyclic flows are driven out of the system, i.e. are constituted by emissions or disposals to nature.

Such findings are aligned with previous interpretations of cycling in dissipative systems. Odum (1969) argued that mature ecosystems develop a cyclic structure to store scarce nutrients dynamically, in other words, to *maintain* the level of materials (i.e. nutrients) within the system. In environmental sciences, post-consumer (re)cycling is associated with lower system resource requirements and emissions generation but has not been related to the maintenance structure of the economic system (Ayres, 1996; WRAP, 2010).

The fact that the cyclic structure corresponds to the maintenance structure of the economic system constraints the possible improvements of the resource efficiency of the system. A minimal cyclic structure might be required for the whole system to keep working, especially at pre-consumer level. However, since pre-consumer cycling lowers the macroscopic resource efficiency of the economic system, a trade-off between improving the resource efficiency of the system and maintaining its level of activity exists. This means that while some resource improvements can be achieved through technological change (e.g. to reduce the amount of tools that the forestry sector requires to extract and produce wood, either by improving how the tools are built (product improvement) or by how the forestry sector processes wood (process improvement)), the pre-consumer cyclic structure might not be completely substitutable for more efficient acyclic processes (as in the case of the wooden tools since the forestry sector does not produce such type of products). Section 5.4.1 shows how to calculate the theoretical maximal resource efficiency of the economic system considering different sub-structural cases (e.g. for a system with no pre-consumer cycling).

In this sense, the discussion on pre-consumer cycling is complex since three options for the productive structure are available, and an optimal balance between them must be found, given the feasible technological possibilities. Recalling section 4.4.4, pre-consumer cycling must be encouraged in the case where wastes and by-products are being disposed out of the system (e.g. landfilled). However, pre-consumer cycling must be discouraged when more resource efficient, linear (acyclic) processes are available. This implies that pre-consumer cycling might be preferable to acyclic processes with a low mesoscopic resource efficiency, but the ideal structure would be constituted by acyclic flows with high mesoscopic resource efficiencies. In this sense, it could be useful if LCA studies focussed not only of End-of-Life recycling but also in pre-consumer cycling, specifically by comparing the three material flow management options available at production level described above. This would allow policy makers to develop industrial policies considering the counter-intuitive effects of pre-consumer cycling.

On trans-cycling While characterising the systemic impacts of cycling, it was also noted that another type of cycling — *trans-cycling* — could happen, involving one or several material flows arranged in a cyclic manner, but which do not fall under the definition of re-cycling, understood as converting waste or by-products as primary material resources (c.f. section 4.4.5). So, *trans-cycling* refers in fact to the cyclic exchange of intermediate goods rather than used or waste goods. At pre-consumer level, two types of trans-cycling exist:

- The same material is exchanged in the context of productive flows. E.g., the forestry sector sells wood to the manufacturing sector, which sells wooden tools back to the forestry sector, constituting a cyclic material flow of wood between the forestry and manufacturing sector (c.f. figure 4.8-a).
- Different material flows are exchanged in the context of productive flows. E.g., the forestry sector sells wood to the manufacturing sector, and the manufacturing sector sells metallic tools to the forestry sector, constituting a cyclic exchange of wood and metal between the forestry and manufacturing sector (c.f. figure 4.8-c).

The rationale behind merging two types of material flows to constitute a cycle (e.g. cyclic exchange of wood and metallic tools) lays on the idea that the productive process requires cyclic exchanges to maintain its activity. E.g., the metallic tools are not embedded in the final product of the forestry sector nor necessarily the wood is embedded in the final products of the manufacturing sector (e.g. used for energy or internal purposes), so in both cases the materials are exchanged in a cyclic manner but not embedded in final production. Thus, such cyclic interactions between sectors are required to maintain its level of activity: the forestry sector cannot operate without the metallic tools and the manufacturing sector cannot operate without wood, and this requirement is reflected in each sectoral resource efficiency.

Trans-cycling follows the same efficiency and dissipative rules as conventional cycling, since the emissions and resources associated to cycling flows only depend on the resource efficiency of each sector and the amount of cycling that goes through each sector (c.f. section 4.4). Thus, there is no analytical difference between pre-consumer trans-cycling and recycling.

Also, post-consumer trans-cycling exists but it is not characterised by a complete cyclic path of the material flow. In this case, the material flows are re-introduced in the productive system as a raw material but in a different sector than the one they originally entered the economic system (otherwise it would be considered post-consumer recycling). Thus, no closed (simple) cycle is formed; instead, the shape of the structure resembles an "S" (c.f. figure 4.9): e.g. silicon is extracted to produce a glass bottle, the bottle is recycled after consumer use, re-introduced in the cement industry to produce cement, and leaves the productive system as cement. So, post-consumer trans-cycling refers to post-consumer re-cycling that does not create a cyclic path. This leads to problems when characterising post-consumer cycling since this post-consumer trans-cycling would not be captured by the algorithm developed in section 4.2.1, since it does not create cyclic paths. However, this issue falls beyond the scope defined in this research, since only the productive structure of the economic system was analysed to assess exclusively the systemic effects of cycling.

Previous studies on recycling have overlooked *trans-cycling* because (re)cycling has been traditionally understood as the re-use of a single substance as primary or secondary resource. Consequently, cyclic exchanges of intermediate goods involving a single or different materials have been neglected. Typical examples of this approach are the substance flow analyses (SFAs) which consider a single substance at a time (Graedel et al., 2002; Daigo et al., 2010). On the other hand, the Economy-Wide Material Flow Accounting (EW- MFA) considers aggregated material flows (Eurostat and European Commission, 2001). However, in this case, the sectoral interactions are not captured (i.e. a given amount of material flows are associated to each sector but it is unknown how these sectors exchange the materials). Thus, EW-MFA cannot be used to identify the cyclic structure and, consequently, it has not identified trans-cyclic paths even if tracing aggregated material flows.

The concept of *trans-cycling* implies that the cyclic structure is greater and more complex than the one suggested by the traditional definition of *re-cycling*. In fact, currently, at pre-consumer level, trans-cycling overwhelmingly exceeds cycling of a single material. Pre-consumer trans-cycling of a single substance can be captured just by tracing the intermediate exchanges of material flows, as in the case of a PIOT for a single material. However, in order to capture pre-consumer trans-cycling between several substances, a PIOT aggregating all material flows should be used. Therefore, to capture all cyclic interactions, aggregate material flows should be used. That is why, in order to capture all types of cycling, the illustrative example in chapter 6 is based on a three sector PIOT representing all material flows of the Italian production system. Although trans-cycling had not been explicitly acknowledged previously, some studies have also aggregated different materials when studying cycling (Bailey et al., 2008) or aggregated them using a common unit to characterise the system flow (e.g. different animal and plant species are "reduced" to energy flows in ecological modelling (Hannon, 1973b; Finn, 1976)).

7.2.2 Application: use of the cyclic-acyclic/direct-indirect decomposition as an environmental management tool

The illustrative example developed in chapter 6 is based on the analysis of the physical structure of the Italian productive system (see description of the dataset in section 3.2.2.3). By restricting the analysis to the productive structure, the systemic effects of pre-consumer cycling can be studied without the added complexity of dealing with post-consumer cycling, but with the advantage that the environmental improvements of the productive system apply to the whole economic system, since the productive system is part of the economic system. In other words, if there are resource efficiency gains in the productive structure, the production-consumption system also benefits of these gains. Resource and emission savings can also be achieved by analysing post-consumer cycling (WRAP, 2010) but the idea is to clearly portray the environmental impact and possible structural improvements associated to pre-consumer cycling alone. The physical structure of the Italian productive system is described by the Physical Input-Output Table represented in table 3.4.

First, the product-based decomposition developed in section 4.3 (which uses the IOA findings of section 3.2) is used to assess which final demand induces most emission generation and resource consumption. The impact analysis of the product-based decomposition constitutes a systemic analysis since it determines the resource consumption and emissions generation of the whole economy associated to the production of each final product. The impact analysis is performed at relative and absolute levels, both key to identify possible policy interventions to mitigate human-induced environmental degradation, understood as resource consumption and emission generation, both potentially disrupting the biogeochemical cycles of the Earth System (c.f. section 2.2). The relative impact analysis reveals which final goods and services are most resource or emission intensive. They are not necessarily amongst the major contributors to the total impact of the economic system, but constitute key possibilities to mitigate targeted resource consumption or emission generation due to their concentrated impact. Then, the absolute impact analysis reveals which final goods and services contribute the most to the total impact of the system, i.e. inducing most resource consumption and emission generation.

The relative and absolute impact analysis of the product-based structures helps informing consumer-based policies to mitigate systemically resource consumption and emission generation. The results of the relative and absolute impact analysis can be used in conjunction. For example, in the illustrative analysis provided in chapter 6, the agricultural sector induces relatively more agricultural emissions and resource extraction than the other sectors. Thus, if it is sought to reduce these emissions or resources, reducing the consumption of agricultural final goods would mitigate these environmental impacts more than reducing other final demand products. However, in absolute terms, it is the manufacturing sector that induces most agricultural emissions, thus, another option is to reduce the amount of manufactured goods to mitigate agricultural emissions or resource consumption. So, this type of analysis can inform policies aiming to discourage selected final goods or services to mitigate selected environmental impacts of the economic system. However, such policies are not always feasible and, more importantly, these policies do not induce a decoupling between final production and the environmental impact generated by the production process, since the impact is reduced by reducing final consumption.

Second, the decomposition developed in section 4.5 is used to calculate the different meta-structures (cyclic–acyclic and direct–indirect), and the indicators developed in chapter 5 are used to identify the prevailing meta-structures and their systemic impacts. It is found that the (pre-consumer) cyclic structure dominates the intersectoral flows and, more importantly, the total emissions of the system (c.f. section 6.2.2.1). This explains the difference between the high mesoscopic (i.e. sectoral) resource efficiencies (between 45% and 71%, c.f. section 6.2.1.5) and the low macroscopic (i.e. economy-wide) resource efficiencies of the product-based and complete structures (between 27% and 39%, c.f. section 6.2.1.3): a pre-consumer cyclic structure inducing high level of emissions also requires high levels of resources, reducing the macroscopic efficiency of the system despite high mesoscopic resource efficiencies. In this particular case, the indirect meta-structure had a lower impact on the system compared to the cyclic meta-structure, although it also contributed significantly to the total emissions of the system (c.f. section 6.2.2.2). This type of analysis was not possible with previous methods, since it was not possible to determine which emissions and resources were related to the cyclic structure. Thus, the decomposition developed in this research enables researchers to understand the macroscopic behaviour of the system by studying its sub-structural (e.g. the cyclic structure) and mesoscopic (e.g. the sectoral resource efficiencies) components.

Then, using the indicator set associated to each meta-structure, it was assessed which meta-structure of which product-based structure induced more systemic effects (e.g. overall emissions, c.f. section 6.3.1). Therefore, this type of analysis can be used to identify important coefficients, which represent the exchanged material flows between sectors, taking into consideration their systemic effects rather than identifying important coefficients by analysing its propagated (error) effects as done in economic analysis (Dwyer and Waugh, 1953; Evans, 1954). This difference is important because, as discussed in section 2.4.5.3, the error propagation does not necessarily account for the actual systemic structural change induced by changing a single coefficient. In the illustration, it was found that the cyclic structure of the manufacturing product-based structure induced most emissions. Then, using the circular diagrams developed in section 3.3, three key meso-intensities (i.e. coefficients) responsible for most of the cyclic structure were identified. Based on how these meso-intensities are linked to the other sectors, it was determined which ones would induce a greater improvement on the macroscopic resource efficiency of the system.

So, the analysis of the product-based meta-structures helps informing policies to mitigate systemically resource consumption and emission generation. The analysis helps identifying which meso-intensities (i.e. coefficients) have a greater impact on the macroscopic resource efficiency of the system. Then, in subsequent analyses, policies can be devised to improve the targeted meso-intensity, either by improving the products provided to the targeted sector or by improving the sector's internal transformation processes. This constitutes a producer-based approach, which differs from the consumer-based strategy option of the first analysis. The most important aspect of such producer-based policies associated to the new decomposition developed in this thesis is that they induce an absolute improvement of the macroscopic resource efficiency of the economic system, i.e. the production process is (partially) decoupled from its environmental impacts. However, as noted at the end of this chapter's section "On pre-consumer and post-consumer cycling", these types of improvements might be limited, since the productive system needs a certain degree of pre-consumer cycling to maintain its productive capacity.

A similar type of analysis seeking to mitigate selected environmental impacts (i.e. either selected resource consumption or emission generation) was also performed in section 6.3.2. Instead of identifying the meta-structure of the product-based structure which induced most emissions altogether, it was sought to identify the meta-structure of the product-based structure which induced most emission or required most resources of a particular type. In this case, the assessment exercise was based exclusively on the analysis of the circular diagrams representing the cyclic–acyclic structures of the product-based and complete structures.

To sum up, in the illustrative analysis developed in chapter 6, different alternatives to reduce systemically the emission intensity (or increase the resource efficiency) of the economic structure were identified by characterising the full cyclic structure of the Italian productive system and analysing it. The advantage of the analyses based on the structural decomposition developed in chapter 4 is that, by being able to trace systemic impacts of the cyclic and/or indirect sub-structures, the researcher or policymaker can identify solutions with greater systemic impact, i.e. inducing greater savings in emissions and resources per unit of flow modified.

The suggested structural analysis is novel and differs from traditional approaches because it is inherently systemic, while previous analyses and environmental impact assessment methods could not inform structural change towards a more resource efficient structure. In particular, comprehensive technical and scientific reports focussed on reducing the sectoral emission or resource intensities (IEA and OECD, 2004; IPCC, 2007a, 2014a) but, as demonstrated by this research, this constitutes a limited approach since greater system-wide savings can be obtained by reducing selected intersectoral linkages (i.e. *meso-intensities*) associated with the pre-consumer cyclic structure.

Additionally, the analysis is also novel because it considers explicitly and separately the systemic effects of *pre-consumer* and *post-consumer* cycling, and also because it includes the cyclic exchanges constituting *trans-cycling*. Technical reports and scientific work have so far overlooked the systemic effects of *pre-consumer* cycling. In fact, the misconception on the diverging effects between *pre-consumer* and *post-consumer* cycling stems from the fact that both types of cycling are called the same in scientific assessments (Graedel et al., 2002; Chen and Graedel, 2012; Graedel et al., 2011; Tanimoto et al., 2010; Van Berkel et al., 2009; Chen et al., 2012), in policy definitions (European Parliament, 2008) and governmental initiatives (Yuan et al., 2006; Ministry of the Environment, 2008; Ministry of the Environment and Ministry of the Economy, 2008; IEEP et al., 2010; Scottish Government, 2010).

Previous research could only provide limited systemic insights because conventional environmental accounting frameworks do not represent explicitly the structure of the human-induced material flows. The only systemic LCA-derived indicator describing the total material flows mobilised and transformed by the economic system to produce a selected final good or service is the MIPS (Schmidt-Bleek, 2001; Burger et al., 2009). However, its adoption has been reduced, probably due to the extensive data and work for it to be derived (Ritthoff et al., 2002). Additionally, the MIPS indicator can be calculated using PIOTs, since the economy-wide emissions and required resources can easily be calculated per unit of final product (as done in the product-based decomposition, see section 4.3).

Similarly, physical indicators related to material flows are aggregated in such a manner that the structural information is lost. E.g., the economy-wide material flows accounting (EW-MFA) framework compiles the materials used by a given country and can associate them to different economic sectors (Eurostat and European Commission, 2001; OECD, 2008d,a,b), but it does not reveal the inter-sectoral exchanges of material flows, which are the ones shaping the physical structure of the economic system.

In this sense, the IOA framework arises as the only accounting and modelling framework compatible with the economic and environmental system of accounts enabling structural assessment of the economy. The advancements in IOA developed in this research are discussed below.

7.3 Physical Input-Output Tables: the backbone framework for systemic material flow management

In chapter 3, the different methods that allow the calculation of the disposals to nature (i.e. emissions and waste) and primary inputs associated with a given final demand were compared. It was found that some of the methods (Hubacek and Giljum (2003), Giljum and Hubacek (2004) and the second method suggested in Suh (2004b)) gathered different levels of emissions and primary inputs because they considered emissions exogenous while they are in fact endogenous, since they are related to the amount of intermediate and final goods produced. In the same section, it was shown that only two methods (the first method suggested in Suh (2004b) and the one suggested by Xu and Zhang (2009)) were appropriate to calculate the disposals to nature and primary inputs associated with a given final demand because they calculate the disposal to nature endogenously (see equations 3.12 and 3.13). Additionally, it was demonstrated that the Xu and Zhang method is in fact a new IO model capable of tracing by-products as final outputs. The difference between these two methods was formalised as a change of final output units. However, it was noted that, due to this change of units, the underlying structure of the PIOT (i.e. the technical coefficients matrix and Leontief inverse matrix) resulting from both methods were different and, consequently, the same structural analysis would gather different results depending on which method was used to reveal the physical structure of the economic system.

In section 3.2.3, the physical structure of the economy was analysed indirectly, i.e. without analysing the technical coefficients or Leontief inverse matrix, to find which production of final goods induces more emissions in absolute and relative terms. Then, in section 3.2.4, a backward linkage analysis was performed to illustrate the difference between the two structures associated to the methods from Suh (2004b) and Xu and Zhang (2009) and to further explain the results of section 3.2.3. It was concluded that both methods represent different structures and only Xu and Zhang's model (Xu and Zhang, 2009) is appropriate for analysing the *complete physical structure* of the economy, i.e. including the material flow related to the emissions lost as disposals to nature. This knowledge was used subsequently in chapter 4 to further analyse the physical structure of the economic system by developing the product-based and the cyclic-acyclic/direct-indirect decompositions, as discussed in the previous section (7.2).

Additionally, in section 3.2.5, both methods were generalised to trace several emissions simultaneously. Such an improvement enhances the analytical potential of PIOTs since they can now relate primary resource use to the generation of specific emission types and even relate the generation of different emission types among themselves.

The theoretical discussion of the differences between the two methods is especially interesting for Industrial Ecology, since it makes it possible to analyse by-product (or emission) generation and the physical structure of the economic system with traditional IOA tools. Moreover, these findings can also be used in economic IOA. For instance, since the Xu and Zhang method (Xu and Zhang, 2009) has been identified as a new IO model capable of tracing by-products as final products, it could be used to improve the accounting framework of secondary production (i.e. a MIOT with two related final outputs: primary final goods and secondary final goods) or even to study policies that impose fixed ratios of production, e.g. between domestic and export production (i.e. a MIOT with two related final outputs: the domestic final goods and the final goods for exports).

However, as noted by Weisz and Duchin (2006), further efforts are still required to standardise the framework: e.g. to improve the methodology of translating monetary SUTs into physical SUTs (as suggested by Pedersen (1998)) and on the level of aggregation of the materials traced in each PIOT. Further efforts are also required to develop and standardise methods to include the use of emissions and waste as raw resources, i.e. to trace *post-consumer* recycling of wastes as by-products *within* the *production-consumption structure*[4] (not only *outside* the productive structure as the two reviewed methods do). Several efforts to include the reallocation of waste within the productive structure have been undertaken but none have been adopted as standard: e.g., Pedersen (2004) included waste generation in the construction of the Danish PIOTs but did not represent the recycling between sectors in an explicit manner; Nakamura and Kondo (2009) developed the waste input-output analysis (WIOA) framework to overcome that issue at the expense of having to use intermediate supply and use tables for wastes (WIOA can model the partial or total recycling of waste explicitly, the excess waste being allocated to other waste management sectors such as landfill or incineration).

Additionally, PIOTs are a unique tool for analysing the physical structure of the economy and linking it to its metabolism and related environmental impacts because they enable researchers to explore the systemic impacts of these links (as seen in the illustrative analysis in chapter 6). Other analytical frameworks are unable to represent systemic

[4]The *production structure* to the productive part of the economic system; it includes the extraction of resources and transformation in intermediate and final goods. The *production-consumption structure* refers to the economic system as a whole in the sense that in includes the whole life cycle of materials: the production structure plus the consumption (or use) stage and disposal to nature or post-consumer cycling.

linkages because they are either based on aggregate physical accounts (such as current environmental accounts or Economy-Wide Material Flow Accounts (EW-MFA) (Eurostat and European Commission, 2001)) or non-exhaustive disaggregated physical accounts (usually based on Life Cycle Analysis (LCA) data). So, PIOTs represent the relationships between the different physical flows of the economy in a disaggregated manner and, thus, allow structural analyses that are not possible with either EW-MFA studies, which does not permit the material flows to be related with the sectoral structure, or LCA studies, whose boundaries are variable and which do not necessarily represent the structure of the flows in manner where structural analyses can be systematically performed. This advantage comes at the expense of requiring extensive data on physical production and emissions; however, as Pedersen (1998) suggested, the Supply and Use Tables (SUTs) used for the monetary system of national accounts can be used to construct PIOTs by combining them with LCA data, specifically by finding the proportion of material content of the products listed in the SUT. So, once the monetary SUTs have been compiled, they could be used to systematically build PIOTs for several materials.

Further developments of the PIOT framework could lead to its integration within the system of national accounts, probably by taking advantage of the statistical infrastructure used to compile its monetary counterpart (as suggested by (Pedersen, 1998)) and the EW-MFA framework, which is already implemented in the System of Environmental and Economic Accounts of some countries (e.g. in the UK (ONS, 2008, 2011), following the EU (Eurostat and European Commission, 2001) and OECD recommendations (OECD, 2008d,a,b,c)).

In fact, the physical input-output framework could become the backbone accounting scheme for environmental accounts. The UN guidelines on the system of environmental and economic accounts (SEEA) suggest using the physical supply and use tables (PSUT) framework — the precursor of input-output tables — as the basis for environmental accounting (UN et al., 2003; **?**). According to **?**, pg. 56: “The PSUT framework [...] records all flows between the environment and the economy, and between different economic units, and, where applicable, records flows within economic units”. However, in practice, statistical offices omit this recommendation and only compile selected emissions and material flows following other subsystems of physical accounting (e.g. for energy, water, and materials (**?**, chap 3.4, 3.5, 3.6)), and associate them to the economic sectors in an aggregate manner, i.e. without revealing the intersectoral exchanges of the materials (as in ONS (2014)).

To conclude, the theoretical findings described above plus the structural analysis developed in chapter 4 could rekindle the interest in the physical input-output framework, because they provide a practical application that informs how to reduce the impact of economic activity while maintaining the level of final production. Hoekstra (2010) noted that "the momentum [to produce PIOTs] has been lost because the literature generated few applications that justify the large investments which are involved in the production of a PIOT". This thesis could contribute to reversing this trend, since this research contributes to demonstrating the use of the PIOT framework to inform decisions on how to mitigate systemically the resource requirements and emission generation of the economic system.

7.4 Circular diagrams: a tool for disaggregated structural analysis and pattern recognition

In chapter 3, a circular diagram was devised to represent the economic system to enable researchers to perform disaggregated structural analyses visually (traditional structural analyses such as the backward and forward linkage analysis only provide aggregate sectoral measures of the linkages) and identify intersectoral patterns. These circular diagrams use the flows' width to provide a visual cue of the flows' weight (or flux); in this sense, the diagram is similar to Sankey diagrams (Sankey, 1898; Schmidt, 2008a,b; Cullen and Allwood, 2010). However, the suggested circular arrangement provide the following extra visual cues compared to Sankey diagrams (c.f. section 3.3.2):

- The *external* and *internal* flows[5] of the system have predetermined positions, providing a visual cue for the type of flow: the external flows are represented on the outer part of the diagram and the internal flows are represented on the inner part. So, there is no need to follow each flow out to the system boundary to determine whether it is an internal or external flow.
- All flows of each sector use the same scale and can be easily compared to the total sectoral throughput, represented by the *middle segment*, which is proportional to the sectoral throughput. This feature is key for disaggregated structural analysis since it makes it possible to determine the relative and absolute contribution of each flow compared to the total throughput of that sector.
- The internal and external input and output flows of each sector are always positioned in the same manner with respect to the *middle segment*. Thanks to this ordering, the circular diagram always has the same layout, independently of the number of sectors or system flows, easing the structural analysis.
- The circular representation avoids distorting the analysis due to unconscious cognitive processes. According to Krzywinski (2011, pg. 22), a circular layout is better because a "linear layout of scale has disadvantages of changing focus (regions in

[5]The *external* flow are the ones entering or leaving the system boundaries. The *internal* do not cross the system boundaries and only link sub-system components.

> the center of the image receive more attention), broken adjacency (neighbouring points on a linear scale are separated [after reaching the end of the page or linear discontinuities of the figure]), broken continuity (data tracks are difficult to follow from one edge of the figure to another), and non-uniform data emphasis (center and edge of the axis are not perceived uniformly - the edge implies periphery, which may not apply)".

Additionally, the circular diagrams can be drawn using several options, i.e. customised to assess different structural features. Two layouts of circular diagrams have been developed in this thesis: the *contiguous* and *symmetrical* (c.f. figures 3.3 and 3.4). The former relates all external and internal inputs and outputs to the same *middle segment* and the latter relates them to opposed, symmetrical middle segments (the left one entailing all input flows and the right one capturing all output flows). The visual analysis of a *symmetrical* circular diagram provides the same results than performing a forward and backward linkage analysis on an IOT but without requiring to do any calculations (c.f. section 3.3.3). The relevance of each flow can be assessed either in absolute terms or in relative terms. For that purpose, the diagram can be either drawn with the actual values of the sectoral throughputs and flows, or each sector and flow value can be normalised. The former enables the researcher to observe the absolute relevance and distribution (structure) of the flows while the latter reveals the relative relevance and distribution (structure) of the flows. The internal flows can be sorted in decreasing or increasing order, allowing the researcher to identify structural patterns in the input or output flow structure. Also, the flows are colour coded according to the sector to which they belong, easing the identification of patterns. However, more sophisticated colour codes can be used, for example, to differentiate between different types of flows. This feature is equivalent to examining two different IOTs simultaneously and capturing their structural relationships. In the illustration, this feature is used to represent simultaneously the cyclic and acyclic structures in a single circular diagram (c.f. figure 6.7).

The suggested circular diagrams constitute a more sophisticated visualisation framework of systems' interactions compared to previous visualisation tools. They share the idea to convey visually the flow intensity as in Sankey diagrams but the circular diagrams provide a more generic and orderly framework to represent a system's internal and external flows, as argued above. Circular diagrams exceed the visualisation options of 2D colour coded matrices (Nakamura et al., 2010; Lin and Huang, 2012) because such matrices provide only two types of information: the value of the cell (given by the colour) and the sectoral position (but the flows' weight is not easily compared to the total sectoral throughput nor can be ordered independently to identify patterns[6]). Circular diagrams also exceed the visualisation options of 3D colour coded matrices. In this case, a stack is plotted in each cell and its height indicates the value of the cell. The stack can be colour coded to represent different type of flows. However, the 3D representation is not very suitable because high stacks mask the height of the stacks behind. Usually, the sectors are re-ordered to avoid this issue but then it becomes tedious to re-assess the new structure each time sectors are re-ordered. The sectoral ordering that can be performed in the 2D and 3D is fundamentally different from the flow ordering within the circular diagram. The sectoral re-ordering of colour coded matrices corresponds to re-order the middle segments of the circular diagram; so, the circular diagram has the extra feature to be able to order the inflows and outflows within each sector.

The circular diagrams developed in this thesis can be drawn with Metab-X (c.f. appendix C), the open source software developed during this thesis to perform the structural decomposition to identify the cyclic structure of dissipative systems suggested in chapter 4.

The application examples discussed below prove that the circular diagrams developed in this thesis are useful for the purpose they were devised: allow researchers to perform disaggregated structural analyses.

As a first exercise, the circular diagrams were used to examine the intersectoral structure of each product-based structure of the Italian productive system (c.f. 6.2.1.6). An important feature was observed, impacting the theoretical understanding of structural analyses in input-output analysis (IOA). The product-based and complete structures were found to have the same backward linkages, which were constituted by the same composition of intersectoral flows. This pattern stemmed from the fact that all product-based structures were calculated from the same original Leontief inverse. However, this also implies that the product-based structures differ because only their forward linkages are different. This structural difference supports the idea that a product-based decomposition is required to identify the particular structural features of the structure underlying the production of each type of final good. Additionally, it implies that the product-based structures can be uniquely characterised by their forward linkages.

Then, the circular diagrams were also used in section 6.3.1 to represent simultaneously the cyclic and acyclic structures of a productive system. Analysing the circular diagrams together with the indicators developed in section 5.3, key inter-sectoral linkages inducing greater systemic effects were identified.

[6]In an IOT, each cell value corresponds in fact to two intersectoral linkages: an input and an output. Thus, the IOT representation is a compressed way to examine the linkages; the circular representation is thus more flexible since each cell value is represented by two flows.

To summarise, the circular diagrams developed in this research enable researchers to perform visual analyses (such as backward and forward linkage analysis (c.f. section 3.3.3) or more disaggregated analyses (c.f. section 6.2.1.6)) that could not be performed using previous visualisation options, such as Sankey diagrams or 2D or 3D colour coded matrices. Thus, the circular diagrams constitute an analytical tool that can help performing or complementing conventional structural analyses.

Additionally, this representation is not only limited to the input-output framework but is valid to represent any system characterised by an exchange of flows, both dissipative or non-dissipative. For example, these circular diagrams could be used to represent monetary, traffic, energy, goods, resource and water exchanges between different geographical regions, between the different sectors of the economic system, or between the sub-divisions within a company.

7.5 Towards a comprehensive analytical framework to inform a transition towards a more resource efficient, circular economy

The rationale behind this thesis was to analyse the physical structure of the economic system to find a way to decouple production and consumption from their environmental impacts, i.e. to improve the macroscopic resource efficiency of the economic system. This has been illustrated in chapter 6 by using the IOA understanding developed in chapter 3 together with the decomposition methods, indicators and relationships developed in chapters 4 and 6. Also, several concepts associated to the cyclic structure were developed and mathematically formalised — pre-consumer cycling, post-consumer cycling and trans-cycling —, which made it possible to identify new options to improve the macroscopic resource efficiency of the economic system. The findings of this thesis were related to the pre-consumer cyclic structure and can be used to inform the transition towards a more resource efficient, circular economy, as intended by current environmental and industrial policies of some countries (Yuan et al., 2006; Ministry of the Environment, 2008; Ministry of the Environment and Ministry of the Economy, 2008; IEEP et al., 2010; Scottish Government, 2010).

The methods developed in this thesis allow identifying the meta-structures, the systemic impact of these and the meso-intensities that would have a greater impact on the meta-structures and thus on the macroscopic properties of the system. However, the methods developed in this thesis cannot recalculate the system's structure after modifying the key meso-intensities. So, although it is known how the meso-intensity changes affect the system (c.f. section 5.4), the exact change of the system structure remains unknown. Future research might want to assess with greater accuracy the impact of modifying selected meso-intensities, in which case developing a new method to recalculate the whole structure after altering a given intersectoral flow would be required.

Also, in future research, the analytical framework and methods developed in this thesis could be extended to devise a more comprehensive framework enabling researchers to identify other options to improve the resource efficiency of the economic system. For example, by considering other cyclic components (e.g. post-consumer cycling), including other human-induced material flows (e.g. associated to the Stock-in-Use), or linking the human-induced material flows with the biogeochemical cycles of the Earth System more explicitly. Some suggestions are provided below in order to expand the current framework and methods towards these aims.

Pre-consumer cycling has been fully characterised within this research thanks to the conceptual and methodological advancements developed in this thesis. However, since the input-output framework used did not include post-consumer flows, post-consumer cycling was not characterised. In order to characterise post-consumer cycling, it would be required to endogenise the final demand sectors (e.g. government, household and gross capital formation) within the productive system. Miyazawa (1976) provides a thorough discussion for endogenising a disaggregated household sector within a MIOT. Similar methods could be adapted to endogenise the final demand sectors within a PIOT. Also, the waste management sectors should be disaggregated and included in the same PIOT in order to trace the cyclic paths between the productive system, the final demand sectors and the waste management sector. Previous literature has already developed some input-output tables with disaggregated waste management sectors (Nakamura and Kondo, 2009). The algorithm identifying the inter-sectoral cyclic structure could be adapted to discriminate between post-consumer cycling (i.e. cycles passing through the final demand sectors) and pre-consumer cycling (i.e. the rest of cycling) to create two different arrays. However, a new method should be developed to decompose the new PIOTs (now endogenising the final demand sectors) between the product-based structures. The method to identify the full cyclic structure should also be adapted accordingly. Such changes would enable researchers and policy makers to assess the systemic impacts of post-consumer and pre-consumer cycling simultaneously.

Another possible improvement of the framework is to include the Stock-in-Use (SiU) of the economic system, which correspond to the goods that are not consumed by their use (e.g. cars, buildings, infrastructure). This would enable researchers and policy makers to make a more comprehensive assessment of the human-induced material flows, since the SiU generates emission and waste. Some studies on the material content of the SiU have been performed (Gordon et al., 2006; Chen and Graedel, 2012; UNEP, 2013b). The issue to integrate the SiU within a PIOT is that the dissipative flows associated to the SiU are not related to the final consumption of the economic system. Thus, linear programming should be used instead of input-output models (Nakamura and Kondo, 2009, chap. 3.5.1.2).

In this research, it was assumed that reduced resource consumption and emission generation implied a reduction of the human-induced environmental degradation. However, the PIOT framework could be extended to provide more accurate measures of the different environmental impacts, especially since this thesis has developed a method to account multiple emissions simultaneously (c.f. section 3.2.5). The emission levels could be compared to the environmental impact thresholds for the different substances. To do that, ideally, the PIOT would be transformed in a multi-regional PIOT to capture more localised environmental impacts, and the emissions would be disaggregated by types (e.g. airborne, water-borne). This type of framework would not only trace the material flows going through the economic system but would reveal which material flows are inducing which type of environmental impacts.

Building on the idea to characterise the Human–Earth System interactions, the physical input-output framework could be coupled to an Integrated Assessment Model (IAM). The analysis of the PIOT would provide information on the types and amount of different material flows induced by the economic system. Then, this information could be fed into the IAM to examine how human-induced material flows affect the biogeochemical cycles (BGCC) of the Earth System. The same IAM could in turn provide information on the availability of renewable resources required by the economic system. This type of approach was already suggested within IOA by Daly (1968) and Isard (1972), and have been subsequently applied to study selected human–ecosystem interactions (Jin et al., 2003). However, the mobilisation and transformation rates of the Earth System are related to the stocks (and flows) of substances in the geospheres rather than to the flows alone (c.f. section 2.4.1 and Butcher (1992)). Thus, IAM constitutes a more appropriate approach than modelling BGCCs with the input-output framework.

As a final note, it is important to highlight that the methodological advancements developed in this research and the ones suggested for further research need to be accompanied by an improved statistical effort providing disaggregated, structured data on the different material flows. As noted previously in section 7.3, the PIOT framework, which is a structured accounting framework and can potentially be built for any type of material, had fallen into oblivion (Hoekstra, 2010) despite the recent UN recommendations on compiling the system of economic and environmental accounts (UN et al., 2003; **?**). The methodological and analytical advances of this thesis might help rekindle the interest in the PIOT framework.

Appendix A

Analytical derivation of the emissions and primary resources of a simple cycle

Given a sector with a resource input of a, a self-cycle of b — again the only cycle going the sector — , a useful output of g (e.g. final demand) and a useless output of e (e.g. emissions), the resource efficiency of the sector is defined as in equation 4.21.

However, b generates cycling losses which need to be compensated with part of the input a to keep the cycling flow constant so the input a can be decomposed between the feeding flow c^f and a acyclic flow s. By definition, the acyclic flow s generate the useful output of the system g and the corresponding losses s^l. So, the useless output e can be decomposed between the acyclic losses s^l and the cycling losses c^l.

g is by definition totally an acyclic flow and the efficiency of the system is known, so the part of the input required to produce g can be found as follows:

$$s = \frac{g}{\eta} \tag{A.1}$$

and thus, the corresponding losses are

$$s^l = s - g = \frac{g}{\eta} - g = \frac{g \cdot (1 - \eta)}{\eta} \tag{A.2}$$

From the mass balance of the system, it follows that

$$a = e + g \tag{A.3}$$

$$c^f + s = c^l + s^l + g \tag{A.4}$$

Substituting equations A.1, A.2 and A.4, leads to

$$c^f = c^l \tag{A.5}$$

Which means that the cycle-feeding resources equal the cycling losses, however, they are yet undetermined.

The cycling losses derive from the losses due to the cycling flow b plus the losses derived from the feeding flow c^f; thus,

$$c^l = b \cdot (1 - \eta) + c^f \cdot (1 - \eta) \tag{A.6}$$

Substituting equation A.5 in A.6,

$$c^f = \frac{b \cdot (1 - \eta)}{\eta} \tag{A.7}$$

and, using equation A.5 again,

$$c^l = \frac{b \cdot (1 - \eta)}{\eta} \tag{A.8}$$

Here, the *cycle-feeding flows* and *cycling losses* represented by equations A.7 and A.8 were found analytically and are equal to equation 4.23, which was found using a power series argumentation.

Appendix B

Detailed numerical information for chapters 4 and 6

B.1 Product-based structures derived from table 4.7

The following tables are used for the calculations at the end of section 4.2.3.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	1.64	0	5	6.64
Sector 2	2.21	0	1.23	0	3.44
Sector 3	0	1.64	0	0	1.64
Resources	4.43	0.16	0.41		
Total inputs	6.64	3.44	1.64		

TABLE B.1: IOT representing a the product-based structure of product one derived from table 4.7

Table B.1 contains two simple cycles of 1.64 units between sector 1 and 2 and of 1.23 units between sector 2 and 3, adding up to $TST_C = 2 \cdot 1.64 + 2 \cdot 1.23 = 5.74$.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	0.98	0	0	0.98
Sector 2	0.33	0	0.74	1	2.07
Sector 3	0	0.98	0	0	0.98
Resources	0.66	0.10	0.25		
Total inputs	0.98	2.07	0.98		

TABLE B.2: IOT representing a the product-based structure of product two derived from table 4.7

Table B.2 contains two simple cycles of 0.33 units between sector 1 and 2 and of 0.74 units between sector 2 and 3, adding up to $TST_C = 2 \cdot 0.33 + 2 \cdot 0.74 = 2.14$.

	Sector 1	Sector 2	Sector 3	Final output	Total outputs
Sector 1	0	7.38	0	0	7.38
Sector 2	2.46	0	13.03	0	15.49
Sector 3	0	7.38	0	10	17.38
Resources	4.92	0.74	4.34		
Total inputs	7.38	15.49	17.38		

TABLE B.3: IOT representing a the product-based structure of product three derived from table 4.7

Table B.3 contains two simple cycles of 2.46 units between sector 1 and 2 and of 7.38 units between sector 2 and 3, adding up to $TST_C = 2 \cdot 2.46 + 2 \cdot 7.38 = 19.68$.

Thus, the total amount of cycling of the re-aggregated structure is 27.56.

B.2 Tables of the acyclic–cyclic and direct–indirect decomposition performed in chapter 6

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.725	0.098	0.04	0	1.048	1.911
Man.	0.153	0.435	0.098	0	0.279	0.965
Ser.	0.139	0.015	0.013	0	0.116	0.283
$\mathbf{r}'$	0.894	0.417	0.132			
$\underline{\mathbf{x}}'$	1.911	0.965	0.283			

TABLE B.4: Cyclic structure of the agricultural production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0	0	0	1	1.214	2.214
Man.	0.16	0	0	0	0.065	0.225
Ser.	0.018	0	0	0	0.012	0.03
$\mathbf{r}'$	2.036	0.225	0.03			
$\underline{\mathbf{x}}'$	2.214	0.225	0.03			

TABLE B.5: Acyclic structure of the agricultural production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0.92	2.01	3.666
Man.	–	–	–	0	0.223	0.771
Ser.	–	–	–	0	0.106	0.257
$\mathbf{r}'$	2.93	0.223	0.106			
$\underline{\mathbf{x}}'$	3.666	0.771	0.257			

Table B.6: Direct structure of the agricultural production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0.08	0.251	0.458
Man.	–	–	–	0	0.121	0.419
Ser.	–	–	–	0	0.023	0.056
$\mathbf{r}'$	0	0.419	0.056			
$\underline{\mathbf{x}}'$	0.458	0.419	0.056			

Table B.7: Indirect structure of the agricultural production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.183	0.195	0.019	0	0.481	0.878
Man.	0.079	1.191	0.046	0	0.534	1.85
Ser.	0.039	0.034	0.006	0	0.056	0.135
$\mathbf{r}'$	0.577	0.43	0.065			
$\underline{\mathbf{x}}'$	0.878	1.85	0.135			

Table B.8: Cyclic structure of the manufacturing production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0	0.073	0	0	0.088	0.161
Man.	0	0	0	1	0.406	1.406
Ser.	0	0.007	0	0	0.005	0.011
$\mathbf{r}'$	0.161	1.327	0.011			
$\underline{\mathbf{x}}'$	0.161	1.406	0.011			

Table B.9: Acyclic structure of the manufacturing production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0	0.365	0.666
Man.	–	–	–	0.944	0.813	2.815
Ser.	–	–	–	0	0.05	0.12
$\mathbf{r}'$	0.365	1.756	0.05			
$\underline{\mathbf{x}}'$	0.666	2.815	0.12			

Table B.10: Direct structure of the manufacturing production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0	0.204	0.373
Man.	–	–	–	0.056	0.127	0.441
Ser.	–	–	–	0	0.011	0.026
$\mathbf{r}'$	0.373	0	0.026			
$\underline{\mathbf{x}}'$	0.373	0.441	0.026			

TABLE B.11: Indirect structure of the manufacturing production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0.273	0.16	0.079	0	0.623	1.136
Man.	0.118	0.785	0.121	0	0.416	1.439
Ser.	0.059	0.027	0.084	0	0.119	0.289
$\mathbf{r}'$	0.685	0.468	0.004			
$\underline{\mathbf{x}}'$	1.136	1.439	0.289			

TABLE B.12: Cyclic structure of the services production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0	0.016	0.173	0	0.23	0.419
Man.	0	0	0.502	0	0.204	0.705
Ser.	0	0	0	1	0.698	1.698
$\mathbf{r}'$	0.419	0.689	1.023			
$\underline{\mathbf{x}}'$	0.419	0.705	1.698			

TABLE B.13: Acyclic structure of the services production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0	0.547	0.997
Man.	–	–	–	0	0.351	1.215
Ser.	–	–	–	0.603	0.424	1.033
$\mathbf{r}'$	0.547	0.351	1.027			
$\underline{\mathbf{x}}'$	0.997	1.215	1.033			

TABLE B.14: Direct structure of the services production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	0	0.306	0.558
Man.	–	–	–	0	0.269	0.93
Ser.	–	–	–	0.397	0.392	0.954
$\mathbf{r}'$	0.558	0.806	0			
$\underline{\mathbf{x}}'$	0.558	0.93	0.954			

TABLE B.15: Indirect structure of the services production structure

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	153	141.09	18.39	0	379.28	691.76
Man.	62.8	845	40.4	0	384.93	1333.13
Ser.	32.64	24.58	10	0	46.91	114.14
$\mathbf{r}'$	443.32	322.45	45.35			
$\underline{\mathbf{x}}'$	691.76	1333.13	114.14			

TABLE B.16: Cyclic structure of the complete (re-aggregated) production structure of the whole economy

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	0	48.91	11.61	20	97.72	178.235
Man.	3.2	0	33.6	658	282.07	976.873
Ser.	0.36	4.42	0	67	50.09	121.865
$\mathbf{r}'$	174.68	923.55	76.65			
$\underline{\mathbf{x}}'$	178.24	976.87	121.86			

TABLE B.17: Acyclic structure of the complete (re-aggregated) production structure of the whole economy

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	18.39	317.07	578.3
Man.	–	–	–	620.84	562.76	1948.98
Ser.	–	–	–	40.37	63.12	153.57
$\mathbf{r}'$	335.46	1183.6	103.49			
$\underline{\mathbf{x}}'$	578.3	1948.98	153.57			

TABLE B.18: Direct structure of the complete (re-aggregated) production structure of the whole economy

	Agr.	Man.	Ser.	$\mathbf{f}$	$\mathbf{w}$	$\underline{\mathbf{x}}$
Agr.	–	–	–	1.61	159.93	291.705
Man.	–	–	–	37.16	104.24	361.025
Ser.	–	–	–	26.63	33.88	82.426
$\mathbf{r}'$	282.54	62.4	18.51			
$\underline{\mathbf{x}}'$	291.7	361.02	82.43			

TABLE B.19: Indirect structure of the complete (re-aggregated) production structure of the whole economy

Appendix C

Data reproducibility

This research adheres to the panton principles (Murray-Rust et al., 2010) and, thus, the data developed in this research is made public (see page iii).

All data and media mentioned in this section is downloadable from my github repository, retrievable at https://github.com/a-altimiras-martin.

C.1 Available data and media

1. The source and high-resolution files of the circular digram figures (3000x3000 pixels). See section C.3 for reproducibility.
2. The source files and high-resolution image files of other drawn figures.
3. The dataset for chapter 3 with applied calculations in odt format or raw dataset in csv, follow the chapter operations to reproduce the results.
4. Section C.4 explains how to obtain the data and reproduce the results from chapter 4.

C.2 Reproducibility of the calculations from chapter 3

The dataset analysed in chapter 3 — table 3.4 — was originally extracted from Dietzenbacher et al. (2009) which is based on Nebbia (2000), in turn based on Nebbia (1999).

All calculations were described in chapter 3. A spreadsheet with the dataset and applied operations is available at the web page above.

C.3 Reproducibility of circular diagrams

The circular diagrams have been drawn with Circos, an open source software originally designed to draw the human genome (Krzywinski et al., 2009). The tabular data parsing tools provided by Circos cannot parse data matching the IOT format, so an automated routine has been created for that purpose and integrated within Metab-X — an open source software specially devised to perform the cyclic-acyclic / direct-indirect decomposition developed in chapter 4 and the associated indicators developed in chapter 5, described in section C.4. Next, a brief description of the main features of the software are provided; see the Metab-X documentation for further details at http://a-altimiras-martin.github.io/MetabX/.

The routine to draw circular diagrams (called circos_interface.py) reads the IOT from a data file and generates new data files in the format required by Circos and according to the layout specifically devised in section 3.3 to represent IOTs as circular diagrams. Then, Circos is triggered by Metab-X and the diagrams generated.

Several configuration options can be used to customise the circular diagram:

diagram type merged or symmetrical

scale type normalised or non-normalised

flow colour scheme of intersectoral flows can be associated to the sectoral input, to the sectoral output, or to a given structural decomposition (e.g. one colour for cyclic flows and another for acyclic).

ribbon ordering the internal ribbons can be sorted in ascending or descending order.

In case further customisation is required, the new data files can be manually modified to adjust other specific Circos parameters, also the circos_interface.py routine can be modified to automatically generate different layouts.

The data files required by Circos to draw the circular diagrams used in this thesis can be built by running the example data set provided with Metab-X, which corresponds to table 3.4.

C.4 Reproducibility of the calculations from chapter 6

Metab-X — an open source program licensed under the General Public License v3 (GPLv.3) — has been developed to perform the calculations supporting the kind of structural analysis devised in chapter 6 and to ensure reproducibility of this work. The project page and documentation is at http://a-altimiras-martin.github.io/MetabX/, where the source code can be cloned as a github repository.

The software is written in python and relies on the Numpy package for generic calculations and relies on NetworkX package for network analyses (e.g. to order the IOT topologically, backward_trace.py), it also uses a modified version of the NetworkX 1.6 implementation of the Johnson (1975) algorithm to extract all simple cycles (in new_cycles.py).

The following calculations are implemented in Metab-X:

1. the product based decomposition devised in section 4.3.
2. the new algorithm devised in section 4.2.1
3. the meta-structural decomposition developed in section 4.5.2

First, Metab-X decomposes a PIOT into its product-based structures and, then, applies the meta-structural decomposition to each of the product-based structures. It finally re-aggregates the results into the meta-structural components of the actual structure. Optionally, the circular diagrams associated to the actual and product-based structures can be drawn, as described in the previous section.

Table 3.4 is provided as an example dataset bundled with the source code, so running Metab-X on that file would automatically generate all results presented in chapter 6 and save them as a spreadsheet; it can also generate the data files required to draw the corresponding circular diagrams, and draws them if circos is installed in your system, generating the diagrams presented in this thesis.

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